This device naturally introduces some lag at the controlled temperature, but nevertheless ensures positive make and break.

Whilst not actually of the contact type, a *Cambridge* instrument must be included in this chapter because it employs the movement of the pointer of a galvanometer to perform a somewhat similar operation. The manufacture of this instrument is now discontinued, but a description is, nevertheless, included because of its intrinsic interest as a method which has been found serviceable, and there are instruments of this type still in use.

The galvanometer movement is illustrated in the diagram, Fig. 59. The pointer *N*, attached to the pivoted moving coil *G*, carries at its extremity a differential thermocouple T_1, T_2, which is connected electrically to a moving-coil relay. A small electrically-heated coil or "heater," *H*, is mounted on the movable arm *B*, which is set, by means of a handle, to the point on the scale at which it is desired to control the temperature, an index *I* being provided to indicate the setting. When the required temperature is nearly reached, the thermocouple T_1 arrives opposite the heater, and an electromotive force is set up which tends for the moment to throw the relay arm away from the contact which it will eventually close. As the temperature in the furnace (or other heated body being controlled) still increases, the pointer *N* continues to move along the scale until the

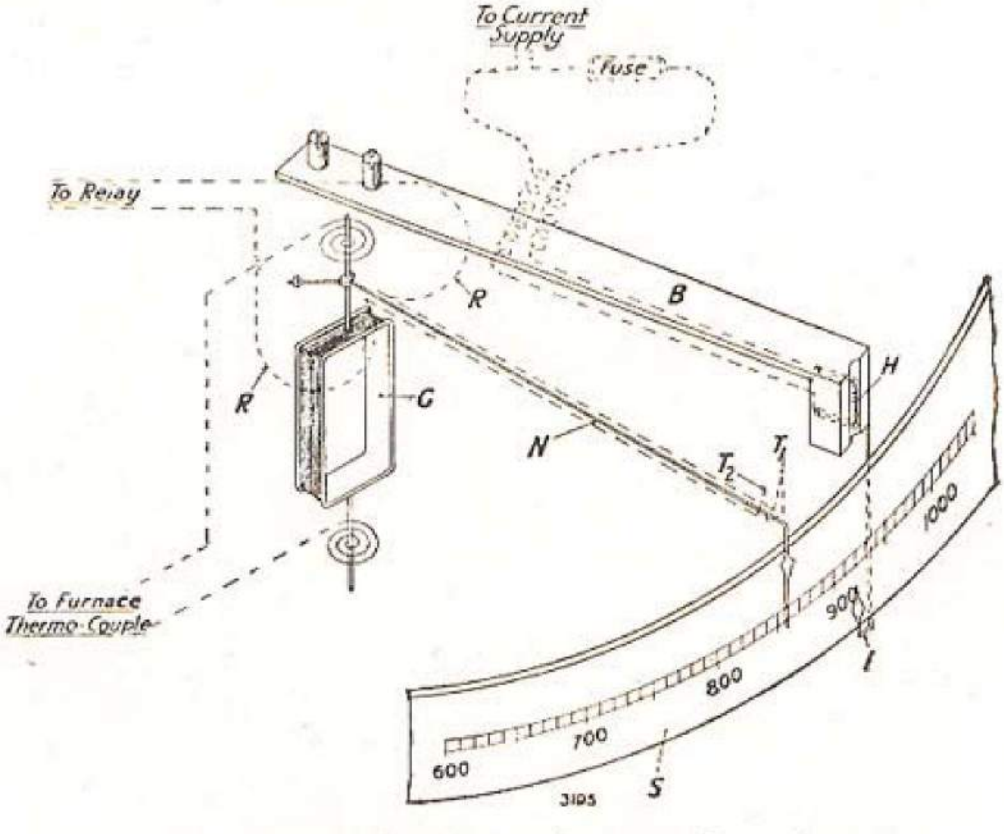


FIG. 59.—Cambridge Pointer-thermocouple regulator.

second thermocouple T_2 is opposite the heater. The electromotive force then generated actuates the relay, closing an electrical circuit which operates a mechanism controlling the supply of heat. Owing to the mass of the furnace, the temperature will probably continue to rise, even though the heat supply is reduced, and the pointer will continue to move up the scale until it meets a stop (not shown in the diagram), where it remains until the temperature falls. As the furnace cools, the pointer N moves down the scale, and when the thermocouple T_1 comes in front of the heater the electromotive force again generated causes the relay to break contact (in case, by any mischance, the contact is sticking), and the supply of heat is thus increased. The pointer N is fitted with an index, so that its position can be seen on the scale; but it will be appreciated that if the temperature exceeds the required value the pointer will not indicate it, owing to the stop. A mirror is usually fitted behind the scale to avoid parallax errors. The heater can be set, and the regulator arranged to control the temperature, at any point between the upper and lower limits of the scale; or the regulator can be fitted with a time-temperature device, as described later. To prevent the regulator failing to function owing to an interruption in the supply of current to the heater, a safety device is provided, whereby the supply of heat to the process being controlled is shut off automatically if the heater circuit should be broken. Alternatively, this device can be adapted to sound an alarm bell or to operate a light or other signal.

The energy consumed by the heater circuit is approximately two watts, and the instrument can be operated from a D.C. or A.C. supply by connecting a suitable resistance or a transformer in the circuit. If an electrical supply mains is not available, the instrument can be operated from a 4-volt accumulator. The regulator can be used in conjunction with a resistance thermometer, thermocouple or radiation pyrometer; the type of element selected depending upon the application for which the outfit is required. When used in conjunction with an electrical-resistance thermometer, the scale of the regulator is calibrated to cover only a few degrees above and below the critical temperature, thus securing a very open scale.

"Chopper-Bar" Type.—In this system an auxiliary mechanism closes the contacts. Two pairs of contacts may be mounted on one table which can be set at any point along the scale, or each pair may be mounted separately and adjusted independently (see Fig. 60). At definite intervals a "chopper bar," actuated by clockwork, electric motor, or an electro-magnet, depresses the temperature-indicating pointer and, depending on the position of the pointer, closes either the "high" or "low" contacts. In addition to temperature indication on the scale and, if desired, also on a chart, a visual indicator in the form of red, green and white lights can be arranged to show when the upper, lower, or predetermined temperature has been reached. The "chopper-bar" type possesses the advantage of permitting free movement of the pointer, except at the short intervals

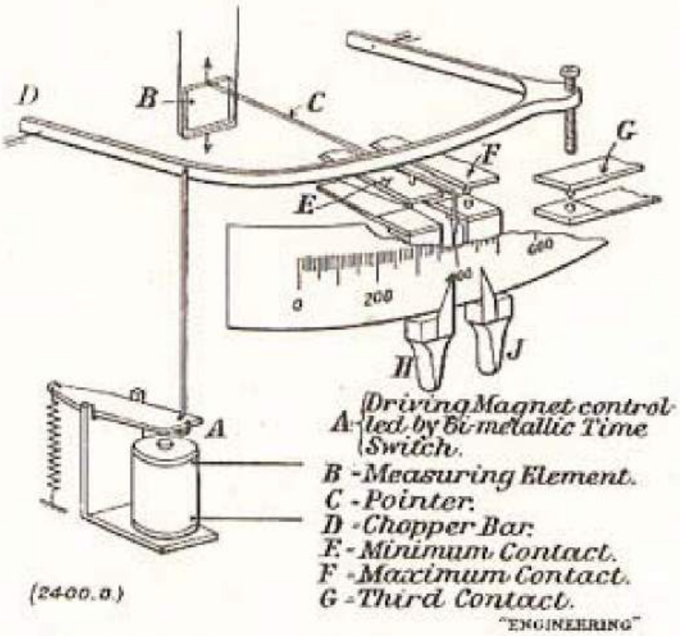
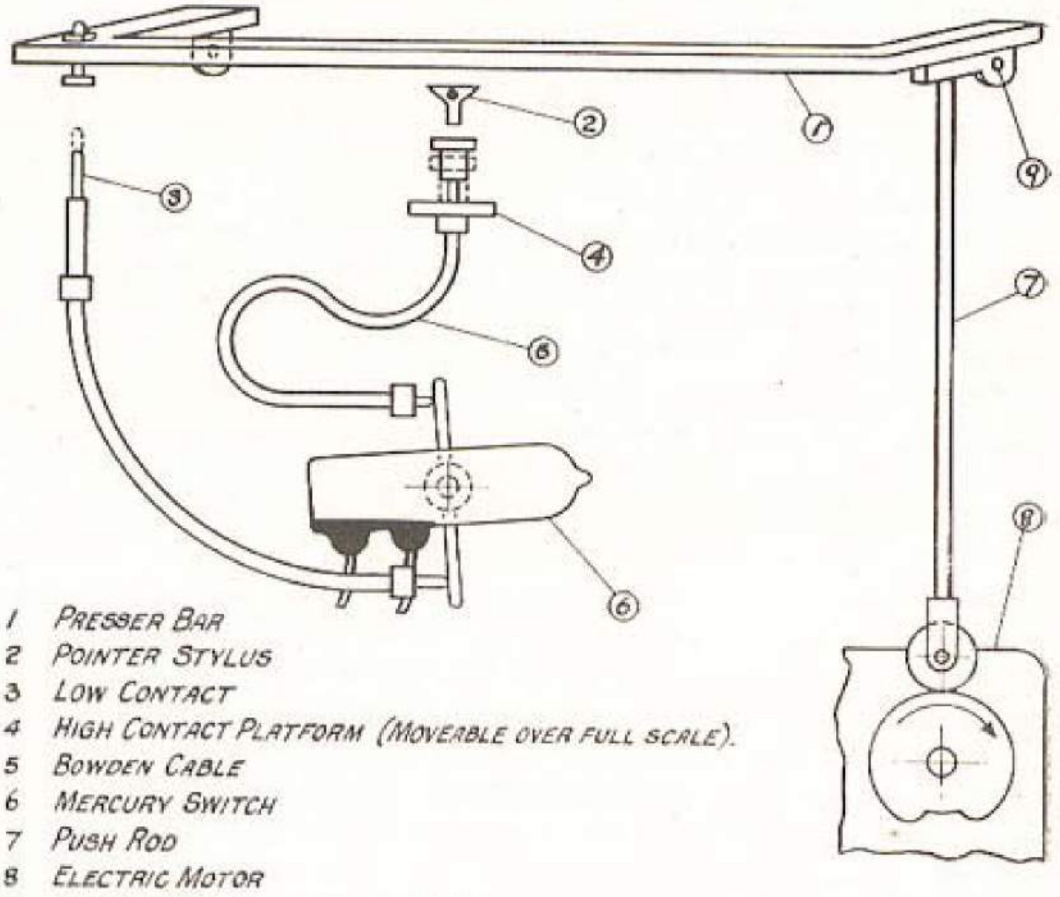


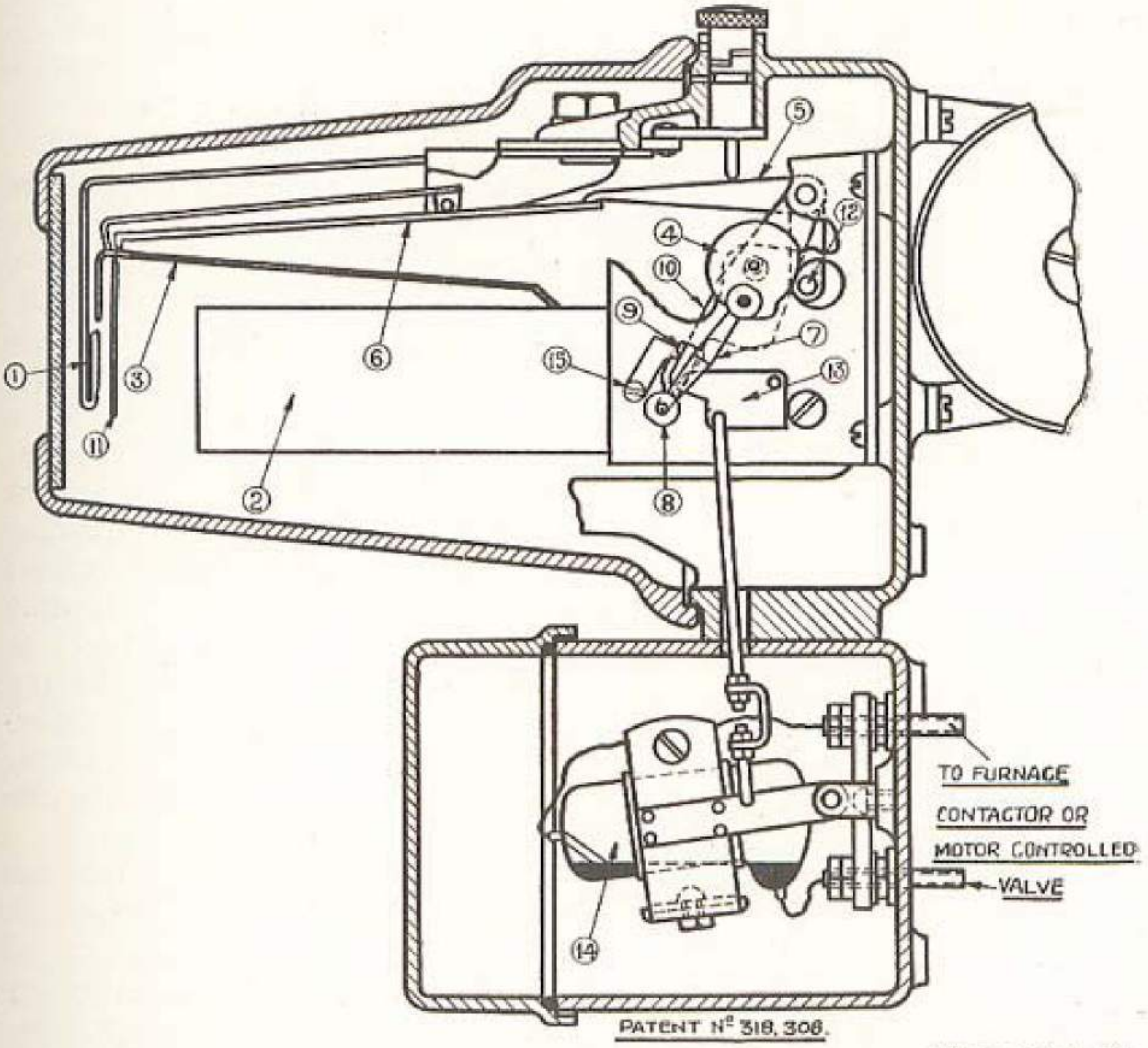
Fig. 60.—Schematic diagram of chopper-bar temperature-regulator.



[Foster Instrument Co., Ltd.

Fig. 61.—Operating diagram of "Flexipush" controller.

of contact. The instrument can be designed so that the temperatures at two points may be controlled by a switching mechanism which connects two thermocouples alternately to the control instrument. The instrument is fitted in this case with two contact devices. Another possibility is that two furnaces can be maintained at the same temperature by a similar switching arrangement with the assistance of two relays, one for each furnace.



[*Electro Meters, Ltd.*

FIG. 62.—Electro Meters regulator.

Instead of using contact tables, a mechanical movement may be used at this point of the instrument, as in the "Flexipush" arrangement of the Foster Instrument Co. illustrated in Fig. 61. The downward movement of the chopper- or presser-bar depresses one or other of two tables, depending on the temperature. These tables are linked, by Bowden flexible cables, to the respective ends of the pivoted support of a mercury switch.

The instrument made by Electro Meters, Ltd., employs a somewhat different arrangement (illustrated in Fig. 62) of the auxiliary mechanism to translate the movements of the pointer into a means of control. The index (1) is set to the temperature at which it is desired to maintain the furnace. The pyrometer consists of a millivoltmeter with a magnet system (2) and indicating pointer (3). A shaft driven through worm gearing from the motor on the back of the indicator rotates a cam (4) which, through the bell-crank lever (5), causes a control arm (6) to be raised and depressed periodically. This cam also acts as a switch-lifting crank, imparting a reciprocating motion to the connecting-rod (7) and pin (8). This pin traverses one of two paths in the slot (9), determined by the extreme angular position of the selector arm (10), and throws the switch "On" or "Off."

Suppose the furnace cold and ready to be started-up. The indicating pointer (3) will be below the index (1). The control arm (6), on its downward stroke, will be free to fall behind the scale plate (11), lifting the bell-crank lever (5) and, through the roller (12), raising the selector arm (10). The pin (8) thus traverses the lower path in the slot (9), catches the trigger (13), and lifts the mercury switch (14) to the "On" position. The switch itself is held in position by a pawl (15), closing the circuit. This switch can be arranged in series with a circuit-breaker, motor-controlled valves, dampers, or similar gear, and maintains a supply of heat to the furnace until the indicating pointer (3) rises just beyond the control index (1). The downward motion of the control arm (6) is now intercepted by the indicating pointer (3), with the result that the selector arm (10) is allowed to fall back, causing the pin (8) to follow the upper path in the slot (9). The pin catches the pawl (15) and, releasing the trigger (13), throws the switch "Off." The circuit is broken and the supply of heat to the furnace is interrupted until the pointer again falls below the control index, when the cycle of operations is repeated.

Regulators of the contact type with galvanometer indicators can be arranged to control rates of heating or cooling. This can be done by suitable movement of the contacts by mechanical means.

An alternative method is to leave the control contacts stationary and introduce an additional electromotive force into the thermocouple circuit.

The advantage of the latter method is that it may be added to any existing automatic-control installation; but its disadvantage is that the readings of the control pyrometer are falsified. An index could, however, be arranged to indicate the amount of additional e.m.f.

CHAPTER XIII

POTENTIOMETRIC REGULATORS.

POTENTIOMETER regulators are closely allied to the indicator or recorder contact types of regulators. Instead of a simple galvanometer to measure the e.m.f. developed by the thermocouple, the e.m.f. is balanced by means of a potentiometer circuit, a galvanometer indicating any momentary out-of-balance voltage.

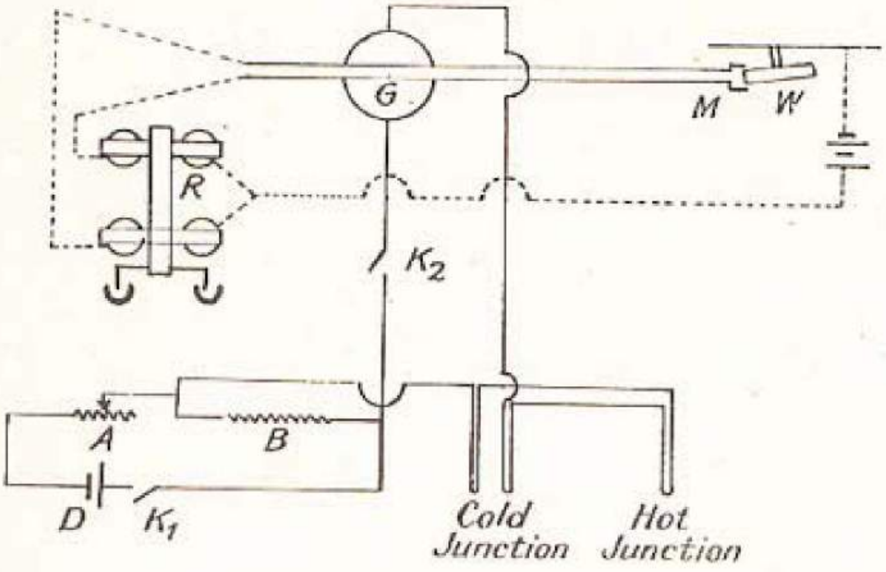


FIG. 63.—Electrical connections of Stockdale thermostat.

A number of forms of potentiometric regulators are available. These instruments are robust and accurate and are used both in the laboratory and industrially. They may be used in conjunction with a thermocouple, resistance thermometer, or certain radiation pyrometers. Normally they are arranged to work upon the potentiometric principle, but when used with electrical-resistance thermometers they are connected in some form of Wheatstone bridge.

Before dealing with the industrial forms of instrument, a laboratory type will first be referred to.

Stockdale's design of instrument is shown diagrammatically in Fig. 63. The thermocouple is balanced by a potentiometer circuit, *D* being the cell, *A* the slide wire, *B* a fixed resistance, and *G* the galvanometer to indicate balance or out-of-balance conditions. The interesting feature of the instrument is the control of temperature by the galvanometer contact. The coil of the galvanometer *G* carries a double boom M, the two parts of which are insulated from each other. The ends of the boom are of platinum and are so bent as to lie closely on either side of a platinum-rimmed wheel W. If the boom moves, one or other of the prongs will touch the wheel, closing a 4-volt circuit and actuating a double relay R. Two resistances in parallel are arranged in series with the furnace, and the relay is in series with one of these resistances; when this resistance is taken out of the circuit by the relay the current to the furnace is decreased.

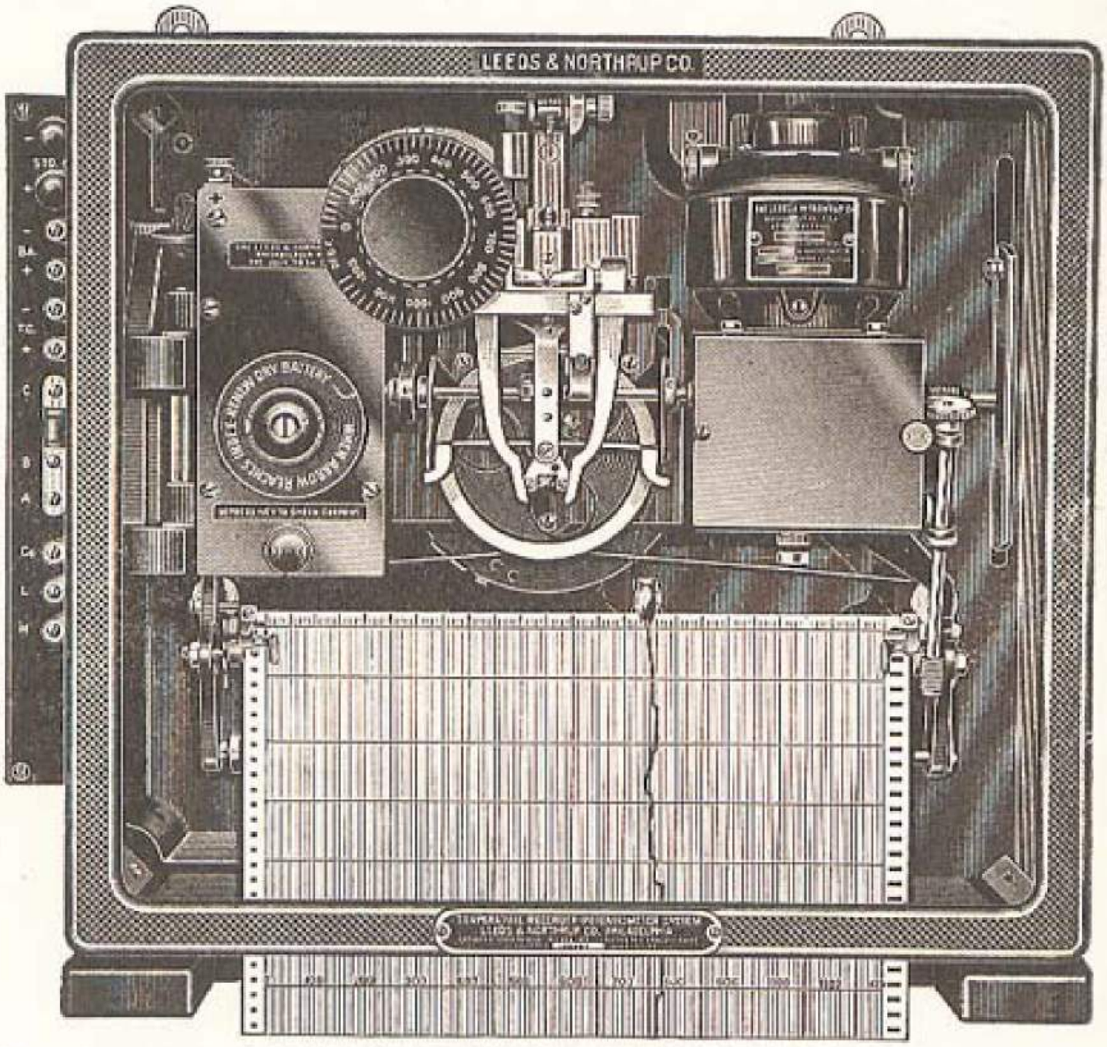


Fig. 64.—Leeds and Northrup potentiometer recorder controller (original design).

The wheel W is made to have a cant of 12 degrees and is driven by clockwork at a speed of one revolution per minute to make the action more lively. The prongs are placed so close that the slightest movement makes contact. Each prong normally touches the contact wheel for 30 seconds, and therefore the high and low currents are on for the same time when the temperature is correct.

The relay is sometimes troublesome because perfect contact between the wheel and prongs is difficult to obtain, and consequently the current actuating the magnets is intermittent. Adjustment has to be made so that the slightest impulse sends the arm either one way or the other. If the arm moves too freely, however, it will rebound off the wheel. This difficulty may be largely overcome by increasing the moment of inertia of the arm, but a better method, involving a little more complication, would be to use a triode-valve relay, and so decrease the contact and current necessary to actuate the circuit.

Industrial Potentiometric Controllers.—We turn now to the industrial type of potentiometer regulators. An important feature of these is the method of mechanically balancing the circuit. As an example of the principles of the method employed, the original design of the Leeds and Northrup instrument (Fig. 64) will be described.

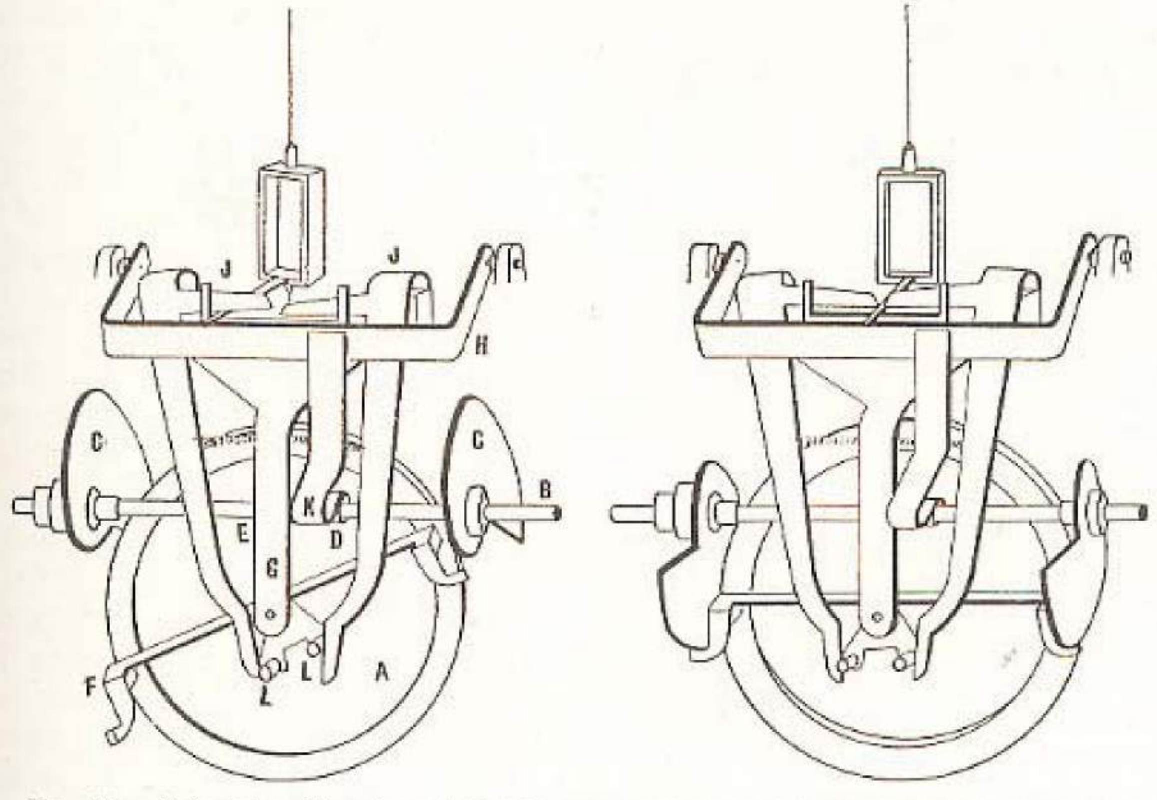


FIG. 65.—Principle of Leeds and Northrup recording potentiometer (original design).

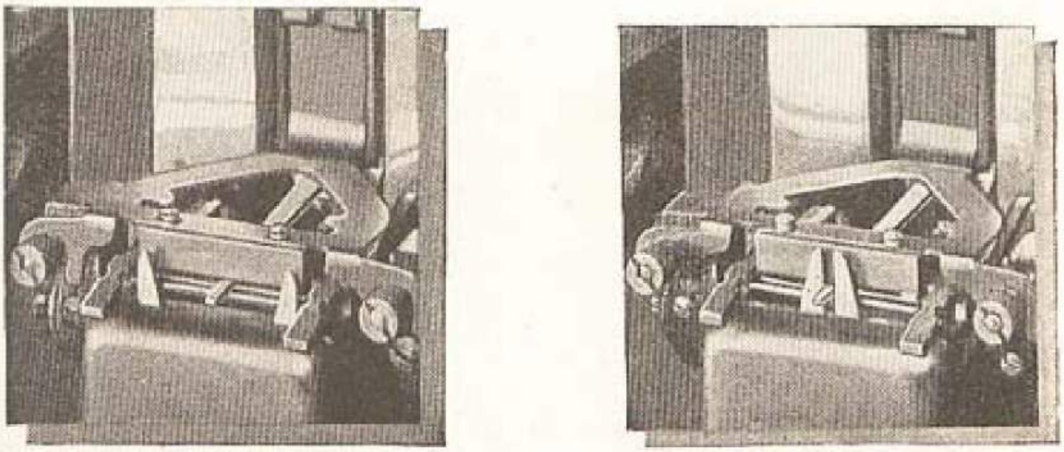
Subsequent modifications in detail have been made, which will be referred to later.

The action is as follows: The disc *A* (Fig. 65) is mounted on a shaft and operates the slide-wire contact by a cord wound on a circumference visible in the figure. The power is supplied by a small, continuously-running motor and enters the mechanical system through the shaft *B* carrying the large cams *C* and the small cams *D* and *E* (*E* being behind *G* in the diagram). At each revolution of the shaft *B*, the cams *C* straighten out the arm *F*, which perchance has been tilted a moment before, and in doing this will rotate the disc *A*, arm *F* being pressed at this time against the disc *A* by the spring *G*. The arm *F* engages in serrations on *A* which prevent slipping. The arm *F* is pivoted on the spring *G*, which is fast to the frame of the instrument. When the cams *C* have rotated until their longest radii are passing the extension of the arm *F*, the cam *E* begins to raise *G*, lifting *F* away from the disc. When *F* is free, the cam *D* raises through *K* the rocker arm *H*, which, in case the galvanometer is unbalanced, catches the pointer under one of the pivoted right-angle levers *J*. One lever is thus made to swing the arm *F* by pressing against one of the concentrically situated lugs *L*. The rocker arm *H* is then immediately lowered to allow the galvanometer to swing freely. Cam *E* is so shaped and fixed on the shaft *B* that it will recede from the spring *G*, allowing *G* to press *F* against the disc just before the cams *C* begin once more to straighten *F*.

The disc *A* moves the contact on the slide-wire. The shaft *B* rotates once in about 2 seconds, which is slow enough to allow the galvanometer time to come to rest, or nearly so. The design is such that the amount of rotation of the arm *F* increases with the extent of the galvanometer deflection, since the pointer approaches the fulcrum of the levers *J* as the deflection increases. The motion of *H* is adjusted so that the rotation of *F* will correspond to a rebalancing step of the pen of $\frac{3}{4}$ in. (19 mm.), when the deflection is a maximum, decreasing uniformly to about $\frac{1}{50}$ in. when the deflection is just sufficient to catch the boom under one of the right-angle levers. This gives sufficient rapidity of the various actions to take the pen the width of the scale in somewhat less than one minute. The position of the pen, when a balance has been obtained just before each record, corresponds to a definite point on the slide-wire, for the pen is fixed to the slide-wire contact. Periodically the thermocouple is disconnected and the standard cell connection automatically made. At the same time the potentiometer slide-wire is set free from its shaft and the clutch engages a second resistance. Movements of the disc then result in changing the resistance of the battery circuit, and the current is thus set to its proper value. The pen does not follow this adjustment and no record is made of variations in the current. A short-circuiting contact on the slide-wire carries the pen to zero on the chart when the battery is run down, thus providing ample warning in most circumstances.

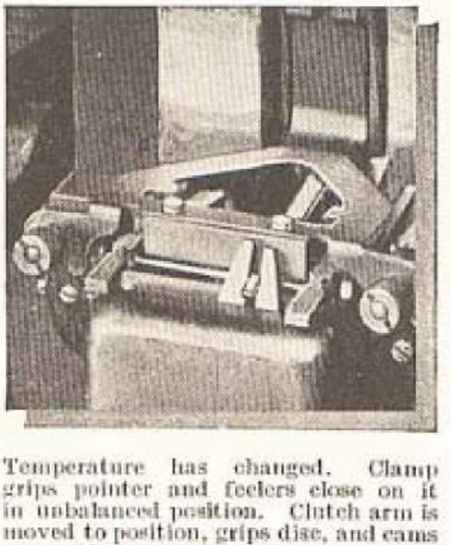
In most of the recent designs of potentiometer recorders the "follow-up" mechanism to move the slide-wire contact is of the scissors pattern. The galvanometer needle is clamped by a cam-operated bar, and whilst held in this position a scissor mechanism closes on it. A clutch is engaged and, being linked with the scissors, rotates the main spindle by an amount proportionate to the deviation picked up by the scissors from the galvanometer needle (see Fig. 66).

Temperature-Control in Potentiometric Regulators.—The control mechanism used in conjunction with the potentiometer types which have been described consists, in general, of a mechanism attached to the same shaft as the disc, and in such a way that when it rotates, contacts are operated. Cam and disc mechanisms are the two alternatives, and the choice between these depends upon the nature of the process to be controlled. Cam-operated control is now, however, little used, as with the gradual slope of the cam it is not possible to produce the necessary rapid make and break of the contacts, the gradual movement resulting in a hesitant make-and-break action.



Here temperature at thermocouple is constant, therefore circuit is balanced and pointer at centre. Pointer is now unclamped and feelers open.

Temperature is still constant. Cushion clamp gripped pointer. Feelers then closed on it and found it in balanced position. Clutch stationary, temperature record constant.



Temperature has changed. Clamp grips pointer and feelers close on it in unbalanced position. Clutch arm is moved to position, grips disc, and cams move sideways and pen to new position.

FIG. 66.—Leeds and Northrup "Micromax" arrangement: details of balancing device.

Disc-operated Mechanism.—With the disc-operated type of mechanism (Fig. 67) the inner and outer radial surfaces of a flange are used to hold the contact open or closed. "Raise" and "Lower" contacts are operated by separate discs, and contact is made or broken with a "snap" action, according to the direction of rotation of the main slide-wire spindle. Either two- or three-position control is possible. The two-position control (Fig. 67) is of the "on and off" type, and in this form the valve or contactor is either in the fully open or shut position. An adjustable by-pass is usually provided with this type of control on fuel-fired furnaces. Two-position control is suitable for furnaces with constant loading conditions.

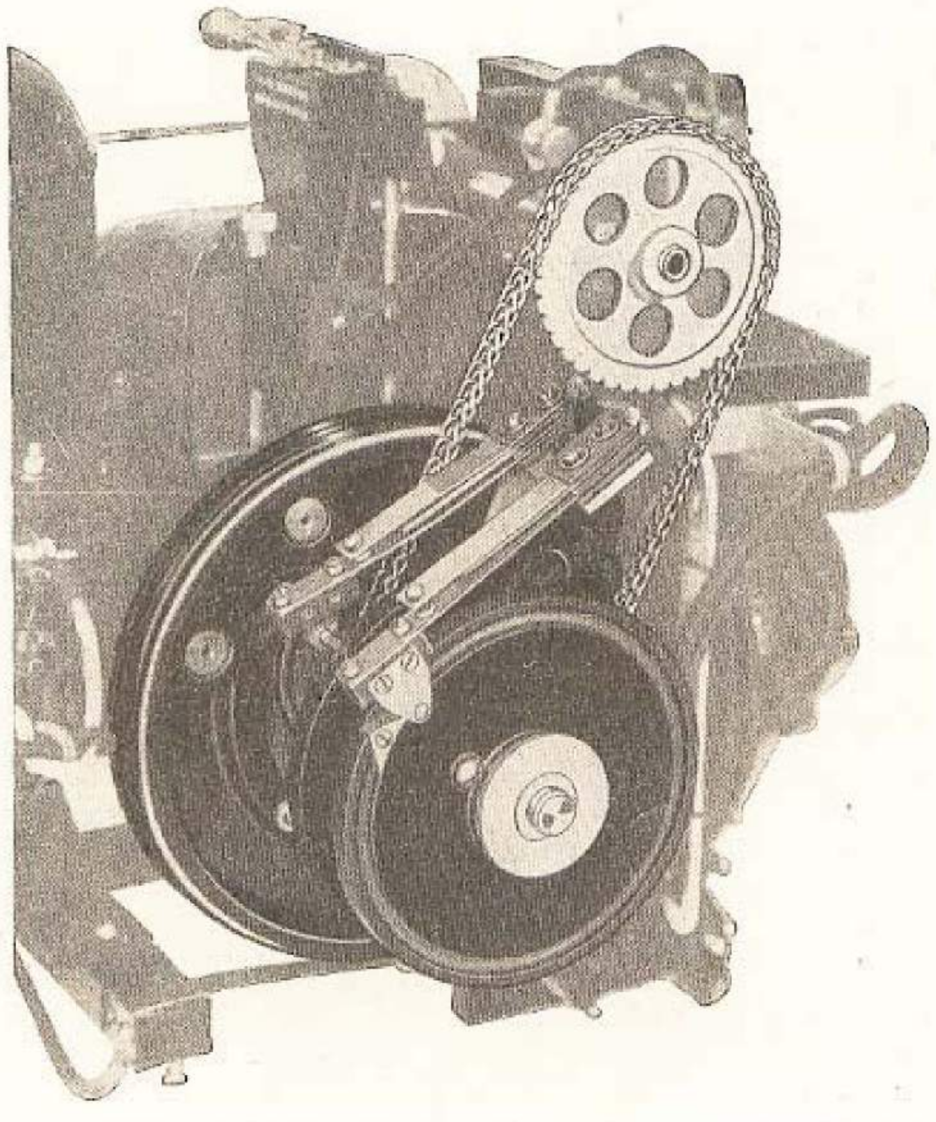


Fig. 67.—Kent regulator: Contacts and cams for two-position disc-operated control.

In three-position control, additional contacts are provided on the instrument and on the motorized valve. Normally the control operates between the intermediate switches. If, however, changes in loading cause a large rise or fall in temperature, the corresponding outer contact is made and the valve is moved to a greater extent in the closing or opening direction. This form of control is particularly suited for furnaces requiring a rapid heat-up followed by a "soaking" period.

Cambridge Non-recorder Controller.—In this (see Fig. 68), the circuit is controlled by a mercury-in-glass tilting switch. A similar arrangement of control mechanism is used to that of the original Leeds and

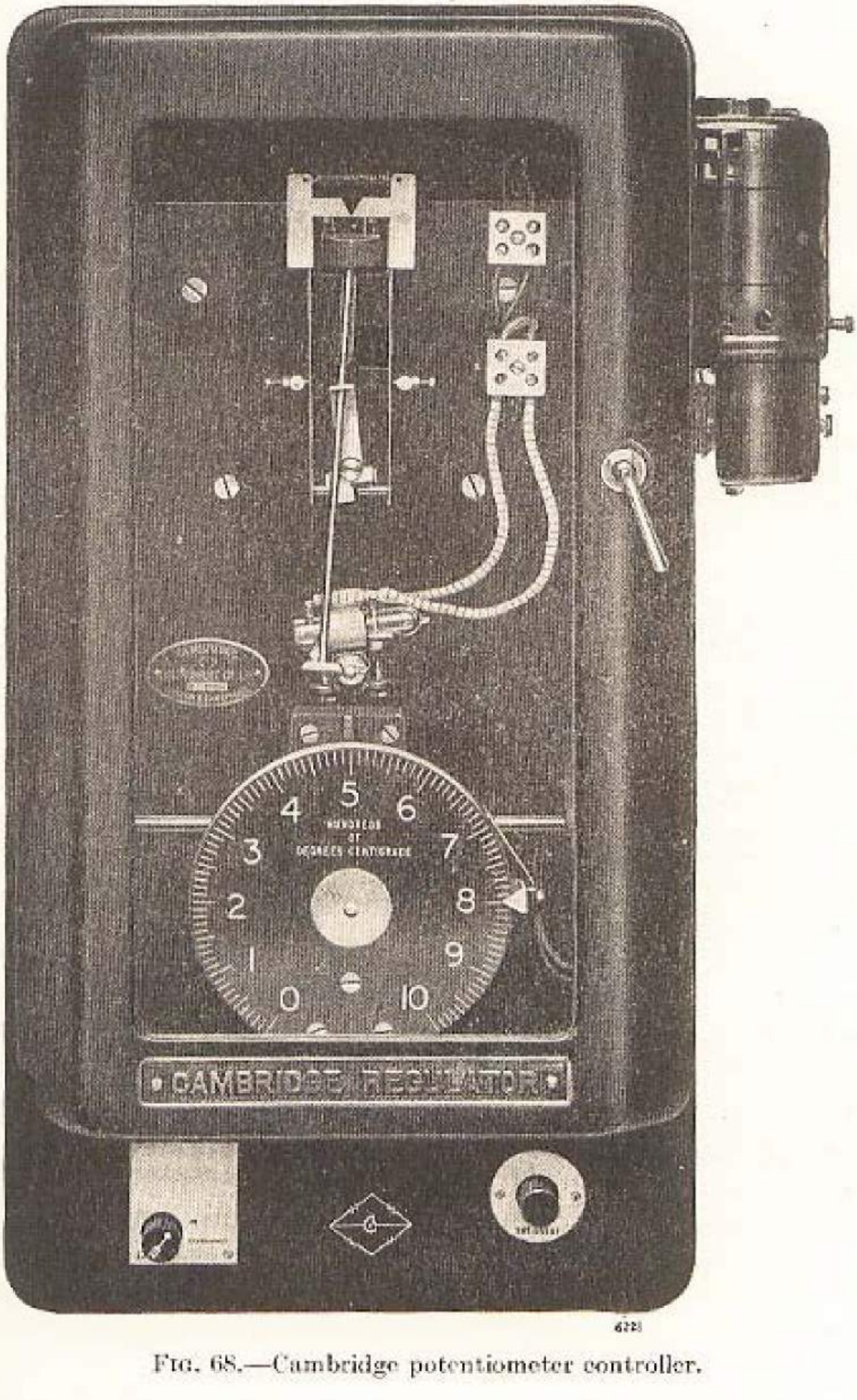


FIG. 68.—Cambridge potentiometer controller.

Northrup design, with certain modifications. The galvanometer pointer swings horizontally below two bell-crank levers and above a clamping jaw or chopper bar, which is periodically raised, thus clamping the pointer against one or other of the levers. Hinged to the clamping jaw is a long tail-rod passing through a guide hole. This tail-piece is deflected to one side or the other by the lower arm of one of the bell-crank levers, if the galvanometer needle is not at zero in the centre. When the clamping bar and tail-rod drop, the bottom end of the tail-rod will tilt a mercury switch in one direction or the other, depending on the way in which the rod has been deflected previously.

Normally the mercury switch is provided with two positions only, *i.e.* with the contacts either made or broken. If desired, however, a two-way tube with a common centre contact may be fitted, which will close one circuit when the temperature is too low, and close another circuit when it is too high, both circuits being open when the temperature is correct.

Mercury-tilting switches are also used in the Cambridge recording controller. The action can be described briefly as follows. The scissors action, already described, rotates a disc which has cam-shaped slots cut in it. Depending on the position of the disc, and therefore of the slots, a mercury switch will be tilted one way or the other. The pivoted holder of the switch has two small vertical projections, one at each end, and one of these may be immediately beneath either a plain or slotted portion of the disc as it descends after the balancing action.

Rate of Deviation.—In some controllers, account is taken not only of the actual deviation from the required temperature, but also the rate of deviation. A relatively large adjustment is made when the deviation and rate of deviation are of the same sign, a very much reduced adjustment, no adjustment at all, or even an adjustment in the opposite sense being made when the deviation and the rate of deviation are of opposite signs, as they are when the temperature is returning to the required value after a deviation.

The instrument designed with this purpose in view by Hodgson and made by Messrs. George Kent is illustrated in Figs. 69-71. A thermocouple is connected to a moving-coil galvanometer in the instrument. The deviation and rate of deviation from the desired temperature are measured at intervals of 20 seconds by a mechanism driven by a constant-speed motor. This mechanism is shown in plan in Fig. 69. The galvanometer needle, not shown in the figure, is situated between the top of a drum and a metal disc extending slightly beyond them, and is firmly clamped between these parts each time the mechanism operates. The normal position of the pointer coincides with the vertical centre-line in Fig. 69, but if any change of temperature has occurred, it will move to one side or the other when released. The two bell-crank levers shown are rotated by the mechanism so that their lower ends close together on to the end of the galvanometer needle, which is by then clamped, and if any deflection has taken place while the needle was free, the drum will be rotated by the pressure exerted on the end of the galvanometer needle. Attached to the drum and rotating with it is a potentiometer slide wire, which moves against a fixed contact, the motion (produced as already explained) continuing in steps until the balance has been restored, when the galvanometer needle will remain in the central position. The total movement of the drum is, therefore, proportional to the change in temperature. The drum is also fitted with a cam of the form shown in Fig. 69, and a roller arm bearing on this cam controls the opening and closing of two contacts which, in turn, control the flow of current to two solenoids. The latter open or close a throttle valve in the fuel-supply pipe to the plant, by mechanism which will be referred to later. The position of the valve is thus dependent on the temperature-deviation from the normal.

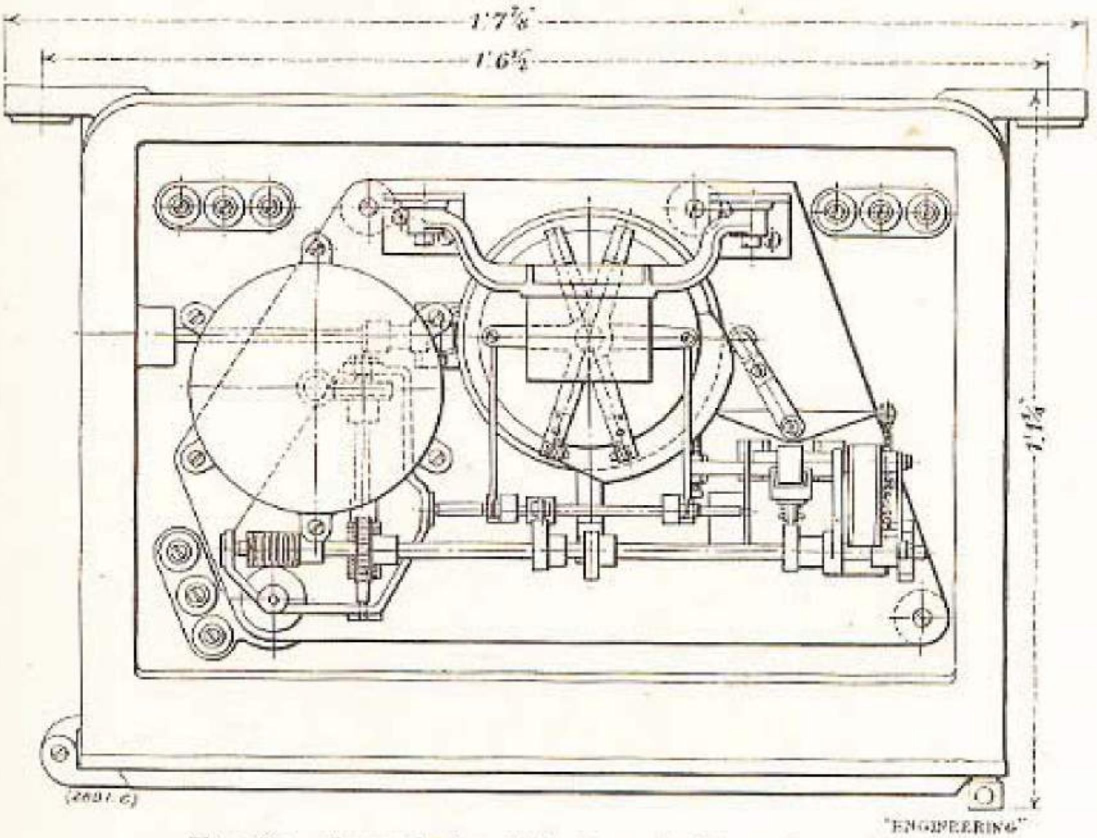


Fig. 69.—General plan of Kent controller and recorder.

The same solenoids are also controlled by two other contacts, the opening and closing of which is dependent on the rate at which a temperature-deviation takes place. These contacts are carried on the ends of the bell-crank levers which close on to the end of the galvanometer needle, as already explained (Fig. 69). It will be evident that which of these contacts is closed will depend upon the direction in which the galvanometer needle has been deflected, *i.e.* upon whether the temperature is rising or falling; and the length of time for which either of the contacts is closed will depend upon the extent of the deflection, *i.e.* upon whether the change in either direction is taking place rapidly or slowly. It may here be mentioned that although the electrical circuits are made by the contacts referred to, they are broken by mercury switches, so that damage to the contacts by sparking is avoided.

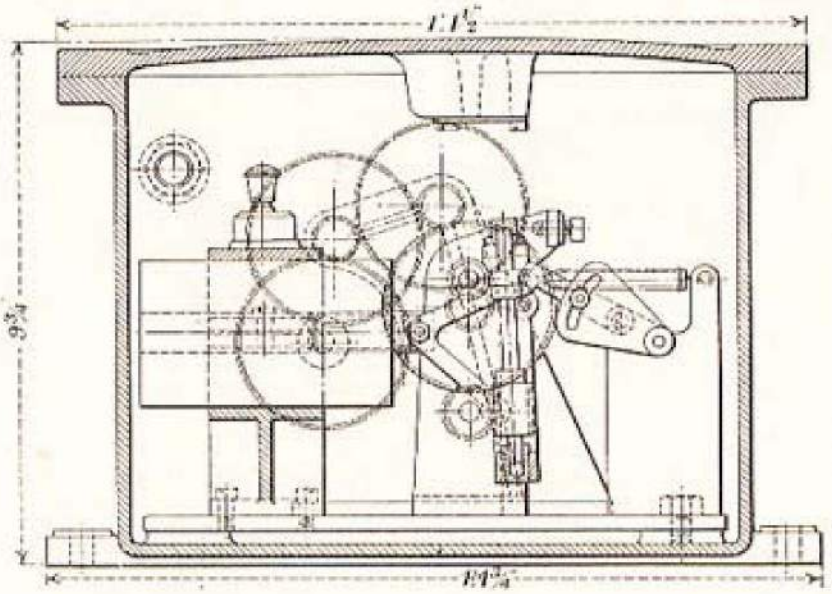
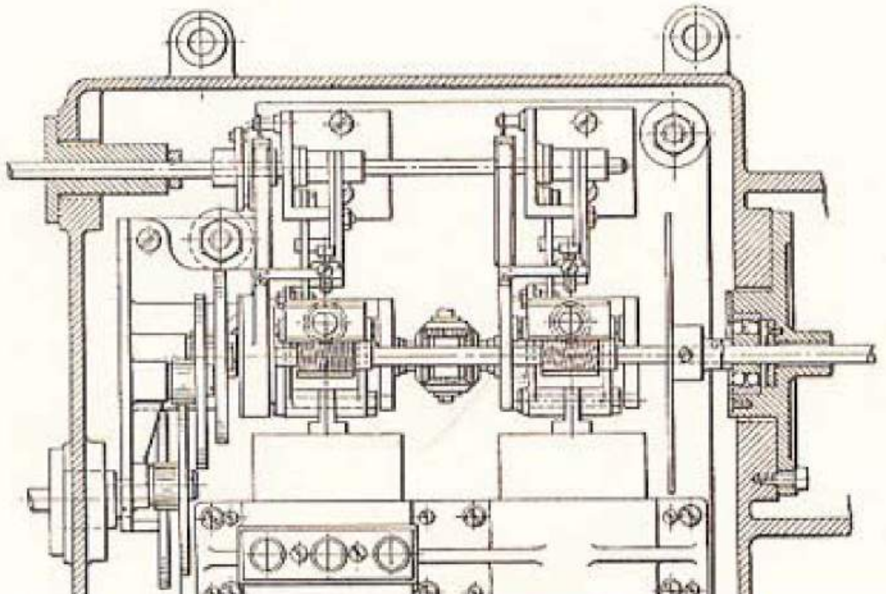


Fig. 70.—Sectional elevation of Kent controller and recorder.



"ENGINEERING"

Fig. 71.—Plan of Kent controller and recorder, showing the two solenoids and connections with control valve.

One of the two solenoids is shown on the left in Fig. 70 and both can be seen in Fig. 71. As will be clear from the former, the plunger of each solenoid is connected to a pivoted frame in which is mounted a spindle, fitted with a worm wheel near its upper end. When one of the solenoids is energized, its frame is pulled over so that the worm wheel engages with a worm on a horizontal shaft, which is driven continuously at a high speed by a small electric motor. The engagement takes place positively and instantaneously without any shock. When one or other of the worm wheels is engaged, the control valve is opened or closed by a train of gears, crank arms and links, as will be clear from Figs. 69 to 71. A differential gear is included, so that if both worm wheels are engaged simultaneously, no movement of the valve takes place; and provision is made for the controls to be inoperative when the valve is opened to a predetermined extent and when it is fully shut. Push-button control, which overrides the automatic control, is also provided.

To minimise " hunting," the Deoscillator of the Foxboro' Company imparts into the thermocouple circuit an additional electromotive force (in either the positive or negative direction as may be required), so as to deflect the galvanometer of the control pyrometer slightly beyond the position it would register in relation to the actual thermocouple temperature at the moment. The temperature indication is therefore distorted at the moments when the anticipating action is taking place. The anticipatory action is adjustable, that is, the temperature below or above the desired control temperature at which the heat input is decreased or increased, respectively, can be chosen.

Reference to Chapter XIII.

Stockdale, *J. Sci. Instr.*, 1924, **5**, 392.

CHAPTER XIV

TEMPERATURE-CONTROL USING RADIANT ENERGY.

THE total energy radiated from an incandescent solid varies as the fourth power of the absolute temperature. If only the radiation which falls within the visible spectrum is considered, however, it is found to vary approximately as the fifteenth power of the temperature (for temperatures in the neighbourhood of 1500° C.). From the point of view of sensitivity, therefore, radiation of energy is a very satisfactory criterion of temperature, since a slight change in temperature produces a relatively large change in energy radiated. It will be readily appreciated that this form of energy should provide a very useful and comparatively accurate means of control at temperatures above 600° C.

Total-radiation pyrometers of the type which develop an electromotive force on exposure to the radiations from a heated body can be used with many of the types of regulators described in other chapters. In fact, they may be used with most forms of regulator with which a thermocouple pyrometer may be used, providing the temperature exceeds 600° C. Attention will not, therefore, be devoted here to this type, but consideration will be given to another form of radiation-sensitive element.

It is well known that if the light from an incandescent body is allowed to fall on a photoelectric cell, a current will be developed which is proportional to the intensity of the light falling upon the cell. As the temperature of the body changes, its brightness also changes, so that if the photoelectric cell current is amplified, it can be used to operate suitable control devices. An image of a definite area of the furnace wall or hot body is focussed in the plane of a diaphragm placed in front of the photoelectric cell, and only the centre portion of the image is allowed to pass through on to the cell. The housing containing the cell may be placed at a distance of three feet or more from the furnace.

The current from the photoelectric cell can be used for control purposes through the medium of delicate relay systems, but a more satisfactory method is to use a "hot-cathode" tube relay ("thyratron tube").

In the apparatus used by Koller[1] the current passes through a high resistance, and the drop in voltage across this resistance is impressed between the grid and filament of the hot-cathode tube (see Fig. 72). As soon as this voltage drop exceeds any predetermined value (that is, as soon as the temperature exceeds a predetermined value), the hot-cathode tube operates and the supply of heat to the furnace is cut off. The furnace then cools down, the photoelectric cell current decreases, and the hot-cathode relay breaks the circuit. The cycle is then repeated.

The control mechanism may be varied to suit the individual needs.

To keep the temperature below a certain maximum, only one hot-cathode tube is required, but by using two tubes both an upper and lower limit may be set.

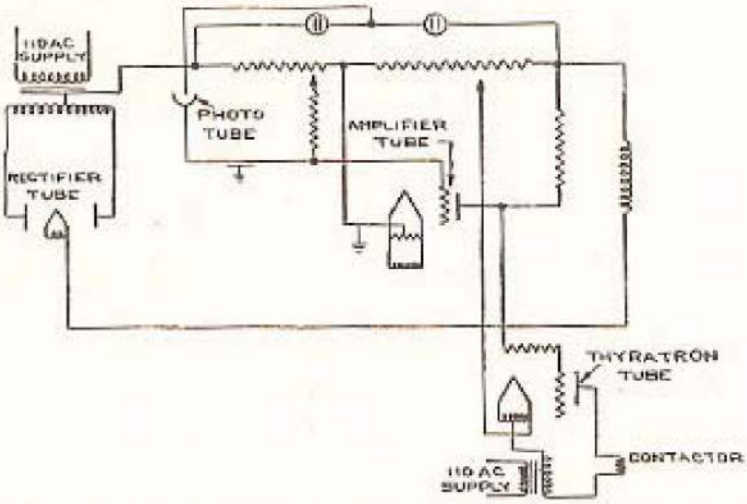


FIG. 72.—Koller photoelectric-cell furnace control circuit.

Amplifier circuit shown above. D.C. resistance-coupled type, making use of a PT-240 pliotron. Rectifier unit built into the set supplies D.C. Voltage on amplifier tube is maintained constant at 180 volts by a pair of glow tubes which absorb fluctuations in the supply line.

The advantages of photoelectric-cell control are that the method can be applied to high temperatures and in atmospheres which are deleterious to thermocouples or resistance thermometers. It can be used to control the temperature of a part of the furnace or of the charge itself.

It will be realized that the possible errors characteristic of radiation pyrometers due to non-black-body conditions, absorption of radiation by gases interposed between the instrument and hot object, etc., must be guarded against.

Reference to Chapter XIV.

Koller, *Ind. and Eng. Chem.*, **23**, No. 12, 1379-1381.

CHAPTER XV

ELECTRICAL-INDUCTION REGULATORS.

INDUCTION regulators can be arranged to maintain either a constant current or a constant energy supply to the furnace.

In principle the Induction Regulator is a transformer built on the lines of an induction motor, and having the important characteristic that, although normally stationary whilst working, the relative positions of the secondary and primary windings can be altered by moving the rotor. This gives to the induction regulator characteristics very similar to those of a transformer having a variable ratio of turns, and since the method of adjustment, namely, turning the rotor, is perfectly smooth and continuous, the regulator has a regulation equivalent to that of a transformer having an infinite number of tappings over the working range. The supply is carried to the primary winding, while the secondary windings are connected in series with the circuit of which the voltage is to be regulated. The primary winding may be mounted on either the stator or the rotor, depending on the output and voltage, the secondary being mounted on the opposite part. As the feeder voltage rises or falls beyond set limits, the voltage-regulating relay closes contacts which energize one or other of a pair of contactors. These in turn control the direction of rotation of a motor and cause it to drive the rotor spindle of the regulator through spur and worm gear, which raises or lowers the feeder voltage as may be required. Directly normal voltage is restored, the action of the voltage-regulating relay causes the motor to stop. In some circumstances, induction time-delay relays are used to energize the motor-control contactors after a suitable time-interval, in order to avoid response of the induction regulator gear to variations in the voltage that are merely momentary.

These regulators are suitable for industrial resistance furnaces and for furnaces of the submerged arc type where the electrodes are stationary.

Fixed-Induction Furnaces.—An ingenious stationary or fixed form of automatically regulated induction furnace has been described by Perrin and Sorrel.[1] This furnace is suitable for use only where the number of heat-treating temperatures required is limited, as it is necessary to use a separate furnace for each temperature. This is not inconvenient in cases where large quantities of steel articles have to be heat-treated at the same temperature. An advantage of this type of thermostat is that no pyrometer is needed. The principle of the furnace is very simple. A muffle or tube *A* (Fig. 73), made of a metal selected according to the temperature required, is surrounded by a non-magnetic conducting material *B*. The latter is made the secondary of a transformer fed by alternating current from the power mains. The current generated in the secondary depends, *inter alia*, on the specific induction of the furnace tube. This current heats up the secondary, and therefore the tube, until the latter reaches the temperature at which it loses its magnetism, when its specific induction falls, and therefore the coupling between the primary and secondary of the transformer also falls rapidly, and less heat is generated in the secondary. So long as the total heat generated in the secondary—when the tube is non-magnetic—is insufficient to keep the furnace temperature above the magnetic change-point, the tube will not rise above this temperature.

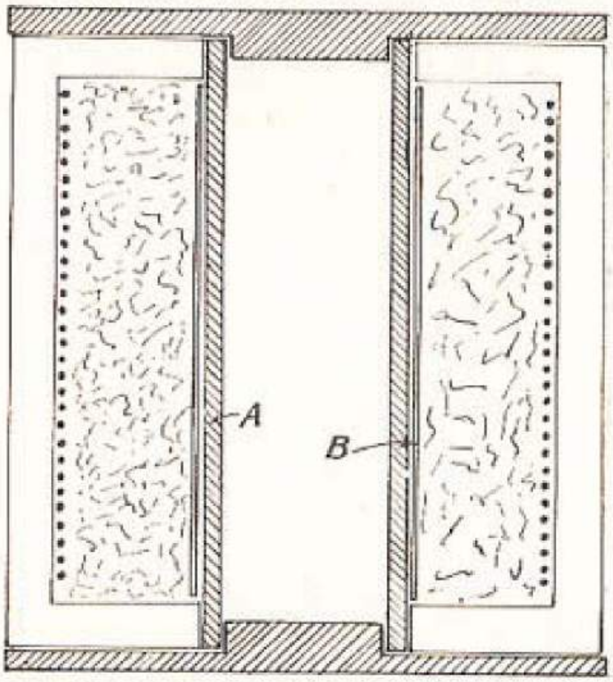


Fig. 73.—Induction furnace with automatic temperature-control.

It is necessary to make the furnace tube of a material [2] which has a quickly reversible change of magnetic property at the working temperature. Materials that have been used are the alloys of cobalt, such as ferro-cobalt which, when suitably selected, can be used for temperatures of from 750° to 1100° C. Below 750° C., ferro-nickel and ferro-nickel-cobalt may be used. The secondary can be made of nickel for temperatures above 350° C., whilst nickel-chrome, copper, aluminium or its alloys can be used for other suitable temperatures.

Naturally the closeness of control will not be so accurate as with some other forms of regulators, but the absence of auxiliary mechanism is a great advantage. The closeness of control will be governed to some extent by the efficiency of thermal insulation, and the size of the furnace.

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(1) Perrin and Sorrel, *Rev. de Mét.*, 1931, No. 8, 448.

(2) Jackson and Russell, *Instruments*, 1938, 11.

CHAPTER XVI

LOW-TEMPERATURE CONTROL.

Cryostats.

THE apparatus used to maintain constant temperatures below 0° C. are termed "cryostats," and can be divided into five general classes, some of which are automatic in action. They are as follows :—

(1) Those employing boiling liquids. This type was largely developed by Onnes at Leiden. Control to ± 0·01° for periods of an hour or so can be effected by regulation of the pressure on a liquefied gas. Any of the following gases are suitable :—methyl chloride, nitrous oxide, ethylene, methane, oxygen, nitrogen, hydrogen and helium. This method is somewhat expensive.

(2) Those involving addition of liquid air to the cryostat bath by hand.

(3) Those in which the flow of heat into a large metal block is regulated, the lower end of the block being intermittently dipped into liquid air. This method is satisfactory if care is taken to place the thermometer and experimental apparatus at identical heat-gradients.

(4) Those in which the flow of heat into the cryostat is regulated by means of a partially-evacuated Dewar flask, which is inside a larger surrounding Dewar flask containing liquid air. This type of cryostat may be made automatic.

(5) The automatic cryostat proper.

In this chapter, consideration will be devoted to the automatic type only.

Principles of Low-Temperature Control.—Automatic low-temperature control involves the use of a means of producing low temperature, a suitable liquid as a bath fluid, and a thermostat. The thermostats employed here are the same in principle as those in use for temperatures above zero, and have been described in earlier chapters. No detailed description is therefore necessary, except where a special feature is involved. Brief reference only will be made to the means of producing low temperatures and the bath liquids used, as these do not properly come within the scope of this book. References, however, will be found at the end of the chapter to some of the more important published works on the subject. The list is not intended to be exhaustive.

A simple method of low-temperature control is to immerse the objects to be treated in a cooled bath of some liquid whose physical properties, such as fluidity, boiling-point and freezing-point, are suited to the working temperature. Regulation can then be effected in one of two ways: either (1) by controlling the flow of the refrigerant, or (2) by setting the flow of the refrigerant for a slight excess cooling, and arranging a thermo-regulator of some form to control electrical heating in order to compensate automatically for this excess cooling. The latter method is particularly suitable on account of the ease of control of electrical heating.

Baths.—Fairly complete lists of bath liquids suitable for use in the low-temperature range are given in the publications of the Leiden Cryogenic Laboratory, and in the Bureau of Standards paper 520; but the following liquids may be cited as being in common use:—

	Temperature-range (° C.)
Brines	− 40 to +120
Paraffin oil	− 40 ,, + 75
Petroleum ether	−130 ,, + 40
Acetone	− 94 ,, + 56
Ethyl alcohol	−114 ,, + 78
Toluol	− 95 ,, +110
Isopentane	−160 ,, + 28
Propane	−190 ,, − 45
Propylene	−190 ,, − 48

An objection to the use of brine is its corrosive action on metal containers. Ethyl alcohol becomes very viscous before it freezes. Propane has to be kept at a temperature below −40° C., or stored under pressure.

Cooling.—The expansion through valves and cooling coils of ammonia, carbon dioxide or other suitable substances, may be used to cool the liquid. Solid carbon dioxide may also be used as a cooling medium. A carbon dioxide slush bath, consisting of solid carbon dioxide with a suitable liquid such as petrol, alcohol or ether, affords a means of attaining temperatures down to about −78·5° C. at atmospheric pressure.

For temperatures as low as −180° C., compressed air may be used as a refrigerant. Liquid air may be utilized by employing either the liquid, or superheated or saturated vapour as a bath, or again by using the vapour or liquid to provide cooling for a thermostat bath. The liquid air should be aged, that is, allowed to remain in the container for about 2 days, since the freshly-made liquid tends to give unexpected fluctuations in the temperature of the bath. Due to progressive concentration of oxygen in liquid air residues, extreme care should be taken to prevent the mixing of these residues with any inflammable substance. Electric motors should be so placed as not to provide a source of ignition for inflammable vapours. If liquid air is used for cooling, the bath liquid can previously be well cooled with a freezing mixture of ice and salt in order to save consumption of the liquid air.

A somewhat unusual method of cooling has been used by Lundstrom and Whittaker.[1] Attached to the wall of the bath, which is made of copper, is a copper rod which is immersed in liquid ammonia or ice, depending on the temperature required. The bath is then cooled by the conduction of heat away by the copper rod. A cooling coil in the bath is therefore unnecessary in this case.

Insulation of the Bath.—As the production of cold is generally a somewhat difficult and expensive process, the insulation of the bath from undesirable access of heat is especially important.

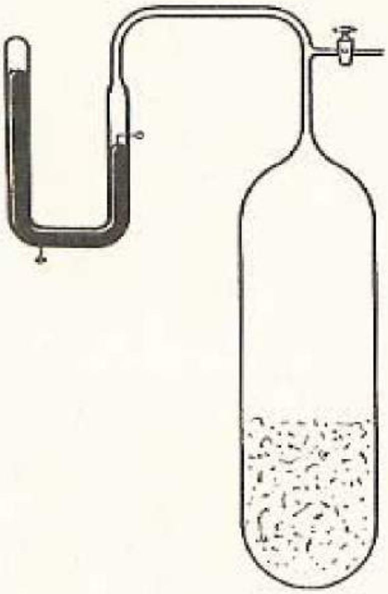

FIG. 74.—A control device for low-temperature work.

The tendency for atmospheric moisture to condense on the bath and its accessories must also be guarded against by suitable insulation.

In the choice of insulators, consideration has to be given to suitability for the temperature, and some materials are very absorbent of condensed moisture and should therefore be avoided. Cork, either in the form of slabs, fine granules or shavings, or hair felt may be recommended. Cork-shavings, a waste product from cigarette-tip manufacture, weigh on the average 3 lbs. per cubic foot. Cork has a thermal conductivity of the order of 0·00008 gramme-calorie per square centimetre per second for a temperature-difference of 1° C. per centimetre thickness.

Thermostats for Low-Temperature Work.—The usual electrical type of toluene and mercury instrument (described in Chapter II) or a bimetallic-strip form (Chapter X) can be adapted for this type of work.

A simple device for observing and controlling low-temperature baths, in which use is made of the absorption properties of charcoal at low temperatures, is shown in Fig. 74. A tube, partially filled with granular charcoal and a gas, is connected to a manometer (a simple U-tube with mercury). The level of the mercury surface will depend upon the amount of the gas held by the charcoal, that is, upon the temperature of the charcoal. Electrodes are sealed in and control the heating circuit through the medium of relays in the usual way. The range of greatest sensitivity is obtained by the selection of a suitable gas in contact with the charcoal, and argon is such a gas. The pressure of the argon may be about 20 centimetres when the charcoal is at room temperature. The space above the mercury in the other limb of the manometer is evacuated.

Forms of Automatic Cryostats.—In the Hearson apparatus for temperatures between −10° and +20° C., the withdrawal of heat is brought about by the evaporation of liquid sulphur dioxide which, after use, is re-compressed and again rendered liquid by means of a small refrigerating plant. The maintenance of any particular temperature depends entirely upon the rate at which evaporation and re-compression of the gas take place, these rates being dependent upon the rate at which the compressing motor works. For the regulation of the speed of the motor a bimetallic thermostat is used.

A cryostat employing pentane cooled by liquid air and capable of maintaining any temperature between −180° C. and 0° C. has been described by Keyes, Townshend and Young.[2] The pentane is contained in an unsilvered Dewar vessel, the vacuum space of which can be exhausted through a side tube. This vessel is immersed in a larger silvered one containing liquid air. The pentane is cooled by the heat flowing across the vacuum space of the inner vessel to a greater or less extent as the vacuum is low or high. The pentane is kept well stirred, and cooling is balanced by supplying heat electrically from a heating-coil in the pentane. The temperature is maintained and controlled by means of a twisted bimetallic strip. By adjusting the pressure in the vacuum space of the inner vessel, and also the heating current, any particular temperature between −180° C. and 0° C. can be obtained. This cryostat is said to be capable of automatically maintaining the temperature constant to about 0·1° C. Finer regulation of the temperature has been achieved by L. C. Jackson [3] by employing the triode-valve relay method.

A cryostat described by Egerton and Ubbelonde [4] (see Fig. 75) keeps the temperature constant to ±0·1° C. down to about −160° C. and does not consume much liquid air. The principle employed is the same as that of the foregoing apparatus of Keyes, Townshend and Young, in that regulation is effected by control of the flow of heat between a metal vessel *D*, filled to a constant height with liquid air, and the bath liquid by altering the pressure of gas in the jacket separating the two. The method of control, however, is different. The lagged Dewar vessel *A* contains the bath liquid. A blower forces liquid air from the Dewar flask *C* through a siphon into *D*, and thereby cooling the bath liquid in *A*. Since there is no danger of the vessel *D* breaking and mixing liquid air with the bath liquid, it is quite safe to use petrol freed from water as a bath liquid. The method of operation is to bring the level of liquid air in the double-walled copper vessel *D* to the correct height, the dimensions of *D* having been carefully chosen for proper functioning by taking into account the amount of heat to be conducted across the heat space and down the walls. The space between the walls is brought to a low vacuum, and the pressure is made such that with the level of the liquid air at a certain height the bath reaches equilibrium at a temperature slightly below the desired temperature. The level is maintained by control of the blower forcing the liquid air over into *D*, this being done automatically as follows. A fine glass tube with splayed-out end is connected to a tambour, on the rubber diaphragm of which rests a lever which makes and breaks the electrical circuit of the blower. The pressure in the tube and tambour is dependent on the covering and uncovering of the end of the tube with liquid air. Provided the rate of stirring is suitably adjusted, the maintenance of a constant level of liquid air in *D* is alone sufficient to keep the bath temperature within 0·5° C., in spite of the change in composition of the liquid air with time. It is necessary only to control the pressure in the air space in *D* in order to obtain automatically a much finer adjustment of temperature. For this purpose the air space in *D* is connected to a water-pump when the bath temperature is a little too high, and to a high-vacuum pump when the bath has been cooled a little below the desired temperature. The normal connection is with the low vacuum, but when a gas thermometer in the form of a thermostat closes a contact, a relay brings the high vacuum into action.

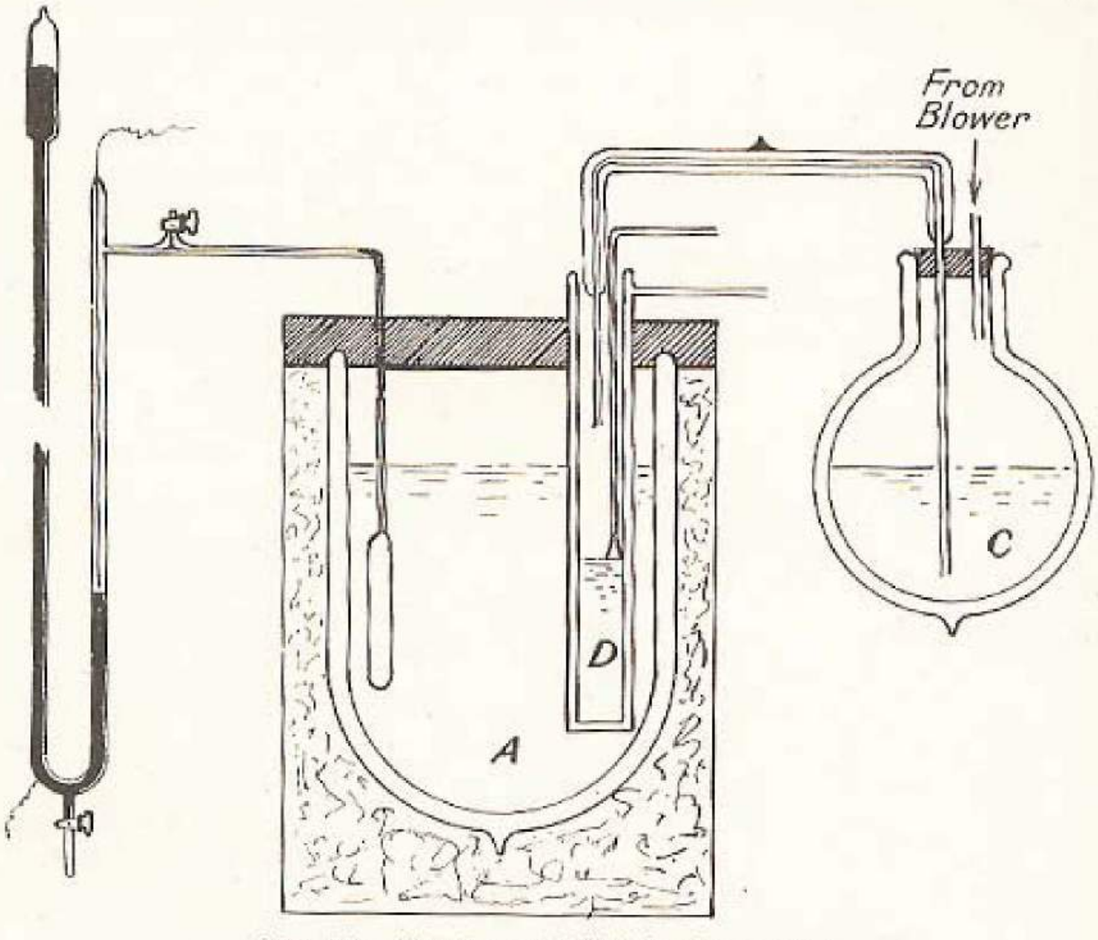

FIG. 75.—Egerton and Ubbelonde cryostat.

An automatic cryostat that incorporates a number of interesting features is that described by Sinozaki and Hara [5] (Fig. 76). The bath liquid, consisting of petroleum ether contained in the Dewar vessel *A*, is cooled by liquid air from the vessel K by means of a cooling coil of copper piping D. Absorption of heat by the vessel K causes evaporation of the liquid air and an increase of pressure. This causes the liquid air either to pass over into the cooling coil or to escape against the water head h. The valve P is controlled, through the solenoid S, by a thermostat G. This consists of a copper vessel filled with liquid pentane and containing a bundle of thin copper strips to improve heat conduction. The expansion of the pentane moves a column of mercury in a U-tube to make and break an electrical circuit, consisting of an accumulator in series with the solenoid S. If the temperature rises, the valve P closes, and when the temperature falls, the plunger drops by gravity and the valve is opened. This closing and opening of the plunger-valve increases and reduces, respectively, the pressure in the liquid-air reservoir K, and consequently increases or retards the flow of liquid air through the vacuum-jacketed tube C into the cryostat bath. The liquid air enters the cooling coil through a jet E in the form of drops, and the amount is such that its cooling effect nearly compensates for, but never exceeds, the heat flow from outside into the cryostat bath. If the gas pressure in the

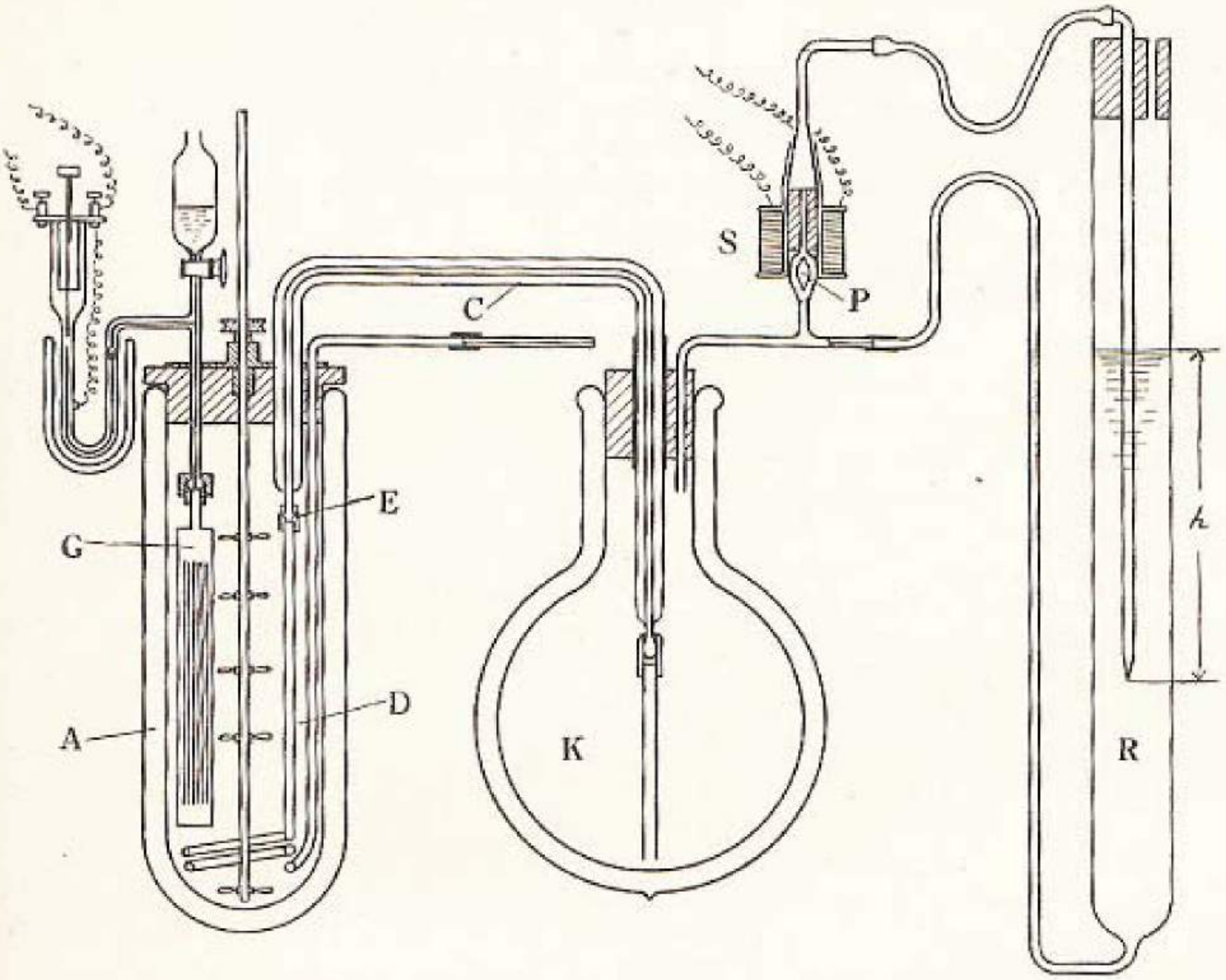

FIG. 76.—Sinozaki and Hara automatic cryostat.

liquid-air reservoir is accidentally increased too much, for example by a stoppage of the jet *E*, the glass tube leading from the reservoir *K* to the bottom of the water tank *R* serves as a safety-valve. The temperature of the bath may be maintained constant automatically from ±0·02 per cent. to ±0·003 per cent. within the range 0° C. to —150° C. for several hours if the apparatus is suitably adjusted. About 3 litres of liquid air are consumed in order to cool down a cryostat of 1,400 c.c. capacity from zero to —100° C. and maintain it at this temperature for nearly 30 hours. Pentane becomes viscid at a low temperature, and is not suitable as a regulator liquid below —150° C. If butane be used for this purpose and for the bath liquid, this cryostat can be used at as low a temperature as —180° C.

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CHAPTER XVII

RELAYS AND VALVES.

THERMOSTATS sometimes operate the cut-off switches or valves directly, but in most cases through the medium of relays. A number of these regulating devices have been described in connection with the particular thermostats. In the laboratory the most valuable forms of relay are the thermionic valve and the hot-cathode, grid-controlled, gas-filled types, to which numerous references have been made in the text. The drawback of complexity is counterbalanced by the high sensitivity that can be attained by their use. The following are cited as further examples of relays, but the list is not exhaustive.

Galvanometer Relays.—Galvanometer movements can be adapted to become sensitive relays for the control of other circuits. The stability of a galvanometer is greater, and it is much more positive in its action than an electronic valve for small voltage changes, as without any elaboration of the circuit it will operate at exactly the same value indefinitely. Again, it is not dependent upon anode voltage or filament current for its sensitivity. It is obvious that the size of the contacts which can be operated by the galvanometer movement is very small, and the current which can be broken must be minute, as any arcing would seal the contacts together. For this reason it is often preferable to control the grid potential for a valve or "thyratron" by the galvanometer relay, and to use the valve to control larger currents. The contacts can be made of fine platinum wire. A wire tongue attached to the moving coil can be arranged to make contact with a fixed wire when the coil is deflected. By using fine wires, sticking of the contacts is minimized, as only a very small surface is in contact. By suitably positioning the wires a rubbing action can be produced. The power required to operate a sensitive galvanometer relay is of the order of 1,000 to 2,000 $\mu\mu$W.

Mercury-in-Glass Switches are now in general use for technical and industrial purposes. Contact is usually established between mercury and mercury and not mercury and metal, in order to avoid arcing with heavy currents and high voltages, which would cause melting of the electrode and leakage at the sealing-point. The leading-in electrodes are contained in pockets in the glass envelope and are covered with a pool of mercury. To prevent oxidation and to keep the mercury clean, the tubes are filled with a reducing gas.

Owing to the small amount of mechanical energy and minimum of movement required to operate such switches, which can break fairly large currents, only a small current is necessary to operate the solenoid. Many forms of switches are available, from the simple form which makes and breaks a circuit (see Fig. 68) to that in which it is possible to make and break two distinct circuits. This latter type is useful where it is required to operate a circuit which controls a cooling medium in addition to the heating circuit.

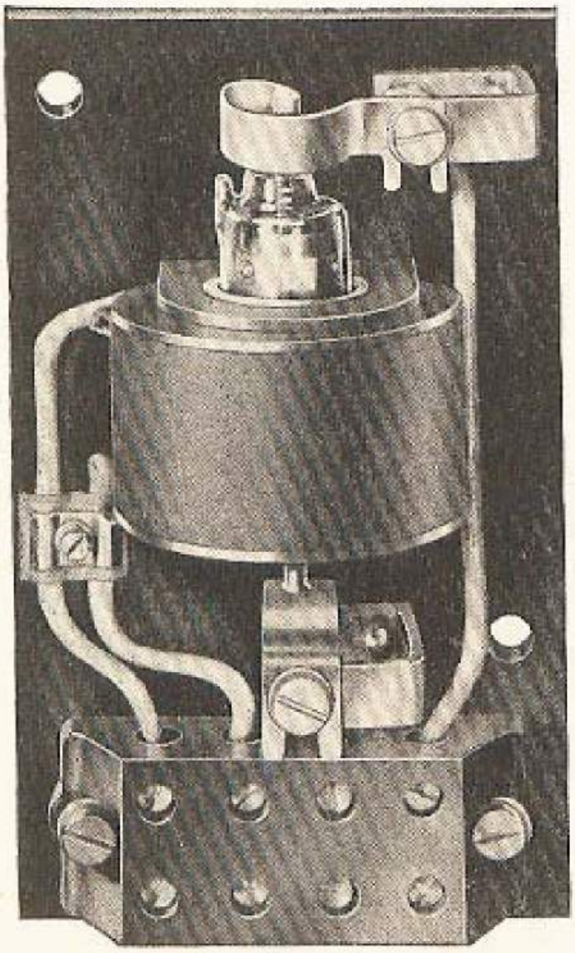


Fig. 77.—I.A.C. mercury-in-glass switch.

A switch of the solenoid type is illustrated in Fig. 77, in which the mercury is displaced by the movement of a core actuated by the solenoid.

Hot-wire Relays.—A simple method of operating a mercury switch in response to impulses from the thermo-regulator is the hot-wire relay of Griffin and Tatlock, Ltd.

The essential feature of the apparatus is a wire supported between a standard and a tensioning screw in another standard. On the passage of a current through the wire, it becomes heated, the expansion causing it to sag. This sagging of the wire is used to effect the tilting of the mercury switch through a link attached to the cradle which supports the switch. One method of setting up the circuit is to connect the thermostat (which may be of any electrical type) in parallel with the wire element. When the thermostat "makes," the wire element is short-circuited, and the current through it being thereby reduced, the wire cools and contracts. The effect of its contraction is to tilt the mercury switch, and thus to break or make the main circuit. By the parallel method of connection, the electrical power broken at the thermostat contacts is much less than when the thermostat is in series with the wire element.

The Sun-Vic hot-wire relay operates on the same principle, but the wire is enclosed in a vacuum tube together with the contacts, which are of the metal type.

An ingenious vacuum switch, manufactured by Siemens and Halske, consists of an evacuated glass tube containing two contact springs sealed in at one end and a flexible corrugated tube sealed in at the other end. Through the flexible tube projects a rod, a slight movement of the outside end of which will cause the inside end to open the contact. The movement of the rod by, for example, the expansion and contraction of a material can thus be arranged to make or break an electrical circuit. The rupturing capacity on a non-inductive load, it is claimed, may be as much as 1,500 volts at 10 amperes.

Valve-operating Gear.—As previously mentioned, the switch may directly control the current to a furnace, or may operate through a motor moving a valve controlling the supply of air, steam, water, oil, etc.

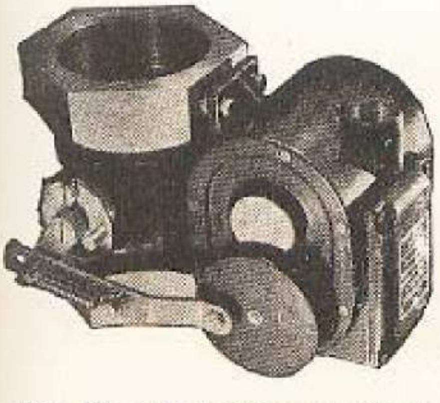


Fig. 78.—Cambridge motorized valve gear for single supply pipe.

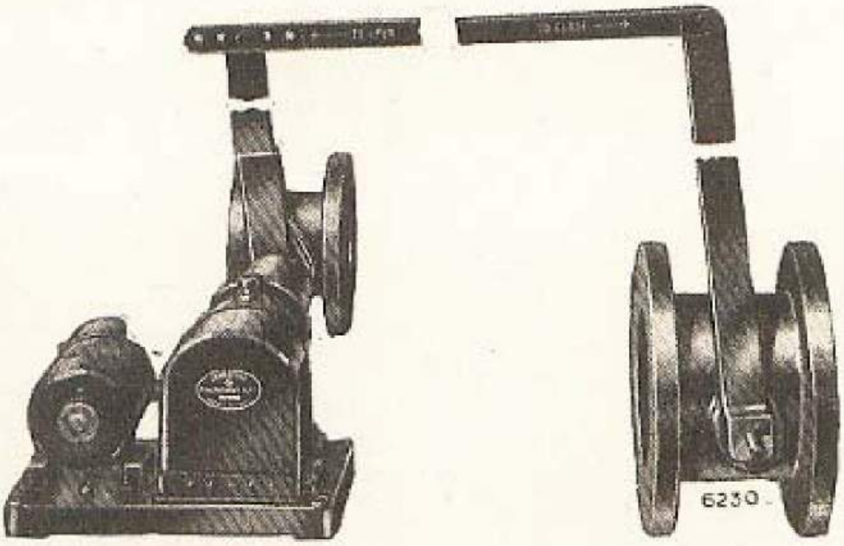


Fig. 79.—Cambridge valve-operating gear.

A simple motorized valve gear for a single supply line is illustrated in Fig. 78. Where more than one valve or damper has to be controlled, a mechanism of the form shown in Fig. 79 may be used. The electric motor is coupled to a speed-reduction gear-box by a clutch adjusted to slip when a predetermined resistance is met, thus preventing the motor or gears from being damaged should a valve stick.

Valve-operating gear may take the form of a power cylinder capable of developing from about 360 to 5,500 ft.-lbs. per stroke. Such cylinders are capable of operating large slides or valves. The thermostatic regulator controls a pilot valve which determines the direction of air, water or oil flow to the power cylinder.

It is sometimes found that the arrangement of the pipework supplying the fuel and air to a manually controlled furnace is such that more than one valve-operating gear is necessary if automatic control is adopted. This entails unnecessary expense, and the efficiency of control is impaired owing to the difficulty in co-ordinating the settings of the various valves so as to ensure the correct fuel/air ratios. By re-designing the layout with the controls in line, it is possible to use one valve-operating gear to control two, three, and sometimes four valves, obtaining, at the same time, improved results.

Valves.

Control Valves.—The selection of a suitable valve for the requirements of an installation requires careful consideration. The material of the valve body and seats will be governed by the normal and maximum temperatures and pressures of the controlled medium. The wearing or erosive action is closely related to the pressures employed and the size of the valve. If, for instance, a single-beat valve is operating in an almost closed position for normal running, and the velocity of the fluid is high, the valve seatings will become "cut." In the case of steam, this causes "wire-drawing."

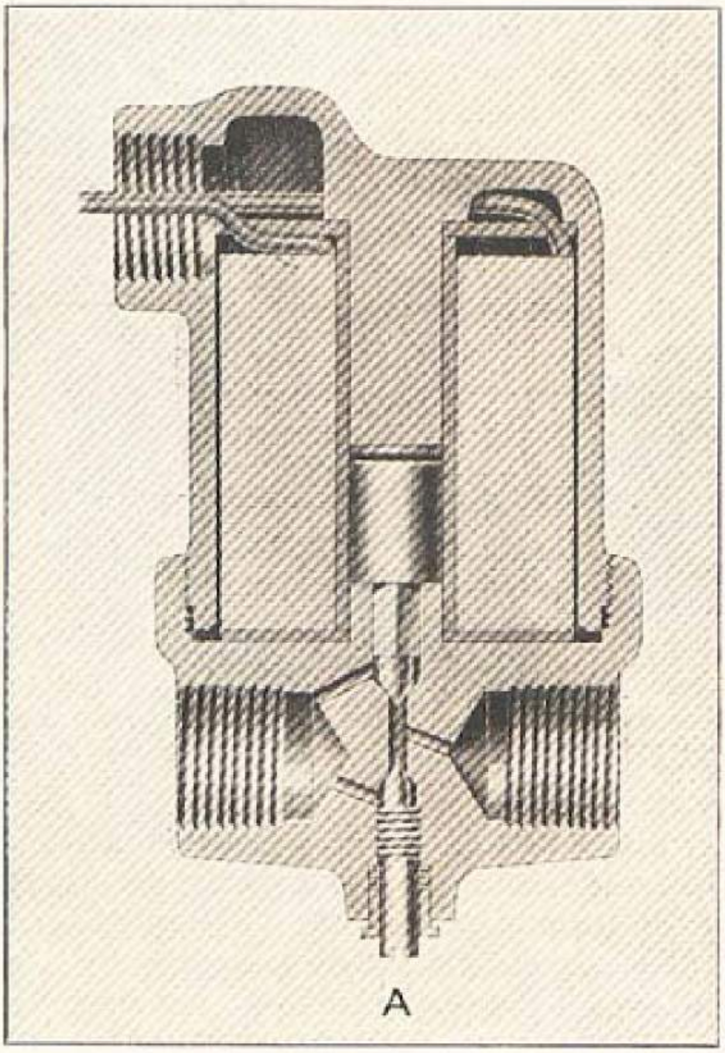


Fig. 80.—"Arco" solenoid valve.

It may be found that a comparatively small valve will give the requisite control when the plant is running but is unsuitable for rapid heating when starting up. By using a larger hand-controlled by-pass valve or a V-ported valve or possibly an on-and-off valve, this difficulty may be surmounted. A large single-beat valve working in an almost closed position will be unreliable, because slight variations of opening will cause large variations of flow.

Solenoid Valves are often used when the controlling device operates electrically. Here a globe- or needle-valve or balanced plunger is normally held open (or shut) by means of a spring. Passage of current through the coil of the solenoid causes the armature to move to the other extreme of its travel, so that the valve is then fully closed (or open) (see Fig. 80). The chief advantages of this type are its low cost and simplicity. It is not as reliable, however, as the motor-operated valve, in which a large operating force is available, which gives better control and more freedom from sticking.

Motor-operated Valves.—In this type, as previously indicated, a geared-down electric motor operates the valve through an eccentric. A single-seated valve is generally used. To prevent overrunning of the motor and consequent opening of the valve, rotary snap-switches break the circuit at each half-revolution.

Diaphragm Valves.—These valves have a diaphragm top, which is operated by an air supply regulated by a valve in the controller. The valve may be of the balanced or unbalanced type, and designed for use with air, water, oil or steam. Wherever possible it should be of the V-port type, as this assists in obtaining smooth control.

Diaphragm valves are of two types, **direct-acting** (single-seated) (see Fig. 81), and **reverse-acting,** in which the disc is drawn up against the seat. The former term usually refers to those valves which close with increase in pressure on a diaphragm. If the line pressure is not too great, single globe valves are used, but for greater line pressure, balanced valves may be needed. The action may be either throttling or "open and shut." In a throttling valve (double-seated V-port) (Fig. 82) the disc or plunger seeks a position where line-pressure drop plus spring pressure balances control pressure and permits continuous flow of the heating medium. Open-and-shut valves are either fully opened or fully closed at all times. They are usually preferred where the temperature-lag in the controlled apparatus is slight or the apparatus itself has a high heat-storing capacity. On the other hand, throttling control is desired where the lag is greater. In general, direct-acting valves are used to control heating media and reverse-acting to control cooling media. The controlling pressure, however, may be used to cause a valve to respond either directly or reversely to a rise in temperature, and hence the choice of valve depends upon whether it is open or shut upon failure of the control pressure. Balanced valves are not usually intended for pressure-tight service.

In some cases a valve has two separate diaphragms. When a cycle controller is used to terminate a heating period, pressure upon the second diaphragm shuts off the heating medium independently of the temperature-control system.

The Drayton Regulator and Instrument Company manufacture a packless type of valve, operated by heat. A metal bellows takes the place of a stripping-box. The valve is closed, on circuit being established, by the expansion of a metal bellows containing a volatile liquid, heated by means of a resistance coil. The operating bellows and heating elements are enclosed in a casing fixed at the top of the valve. The valve opens and closes slowly (within about 2½ to 4 minutes), so that hammer action caused by snap-action valves is avoided. The valve can be used only in low-pressure systems of about 5 lbs. per square inch. For higher pressures a balanced valve with stripping-box must be used.

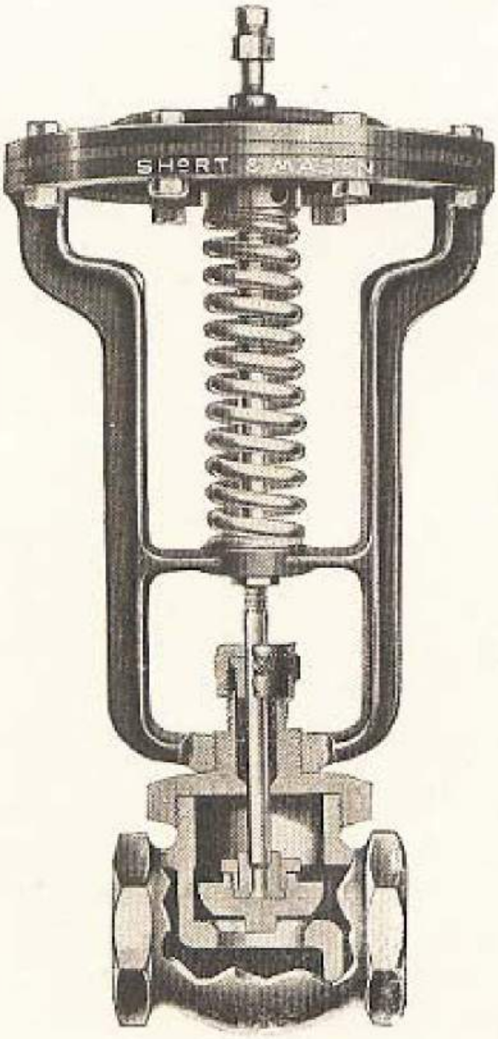


FIG. 81.—Direct-acting single-seated diaphragm valve.

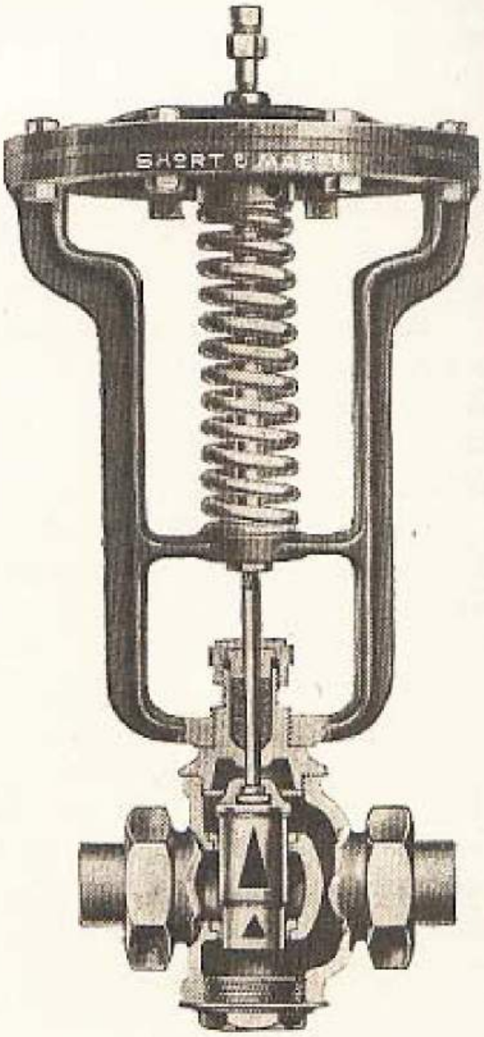


FIG. 82.—Double-seated V-port throttling valve.

Unsystematic Response of the Valve.—Unsystematic response of flow of the heating-supply medium to the thermostat action, particularly detrimental to proportional control, may result from valve errors such as leakage in the control valve or in the by-pass; inaccurate valve position, from friction or from unbalanced valves on fluctuating pressures; and non-proportionality, from the cutting of the valve seat, a greatly oversize valve operating at low lift, a non-proportional or globe valve, flashing in the valve ports, or from limitation of flow by inadequate piping. In the more precise throttling-control installations, where valve changes must be accurate and minute, valve positioners have come into use to eliminate errors of valve friction and unbalance. In every control installation, the control valve must be sized to be the " bottle-neck " of the control-fluid system.

CHAPTER XVIII

CLASSIFICATION OF HEAT-EXCHANGERS.

TEMPERATURE-CONTROL is fundamentally the regulation of heat-exchange. There are, of course, many ways of exchanging heat, and the type of control employed will be governed to a large extent by the system used. A general survey of the various forms of heat-exchangers will, therefore, not be out of place.

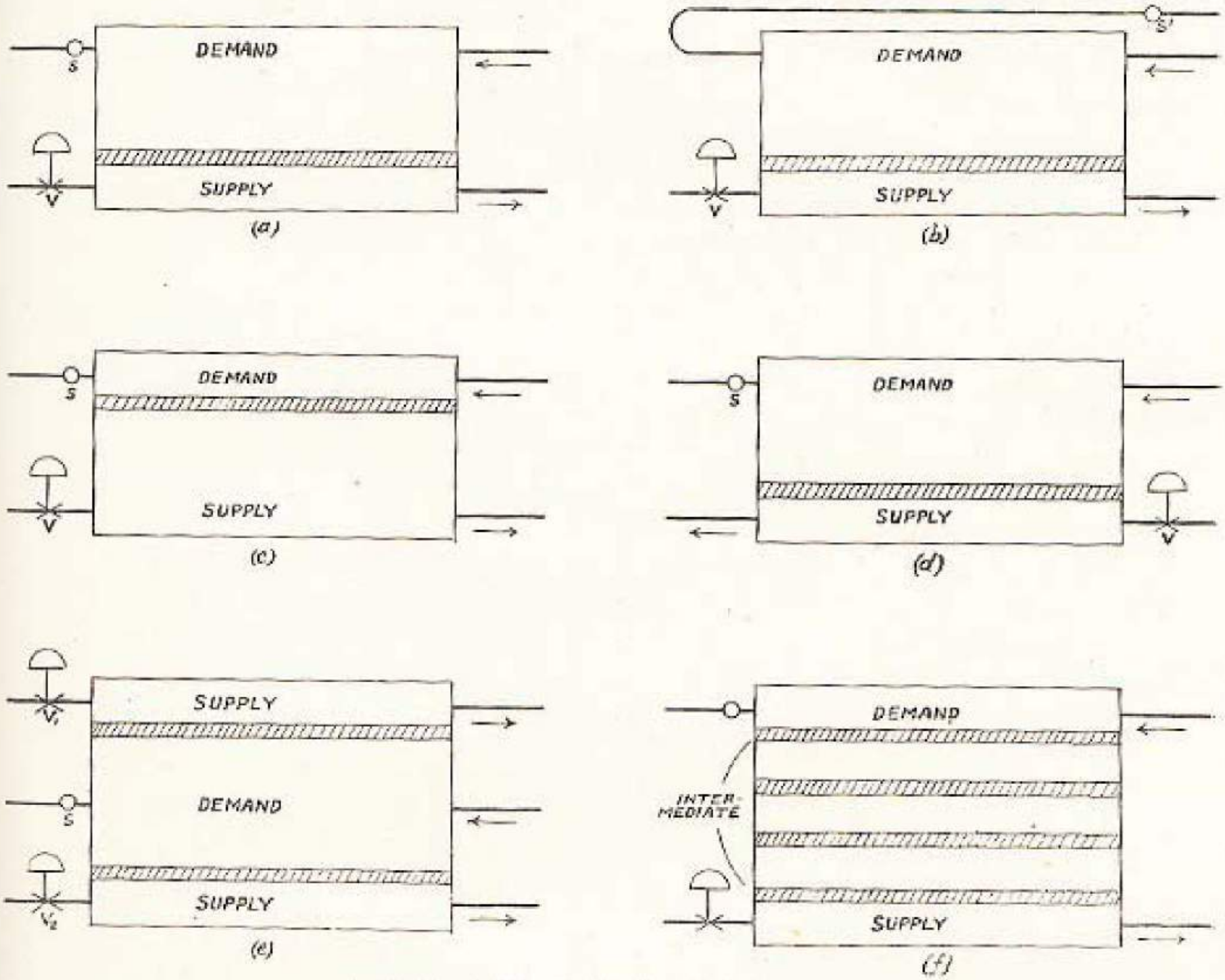
Heat-exchanger design depends on a number of factors, amongst the more important being the quantities of the media involved, temperatures, heat requirements, heat-storage capacities, and the amount of heat-transfer surface and its effectiveness. This effectiveness depends on many factors, but most important, perhaps, are the film coefficients, which are in turn dependent on the media, their temperatures and velocities.

Haigler[1] has classified the various forms of heat-exchangers and represented them diagrammatically. Most of the forms can be represented by two contiguous rectangles, representing supply and demand sides, the length of the common wall signifying the amount of heat-transfer surface, and the thickness indicating the thermal resistance. The width of each rectangular area signifies the thermal capacity per unit of heat-transfer surface, so that each area indicates the total thermal capacity on that side.

The sensitive element of a temperature-controller is indicated by *S*, while the valve *V* regulates the supply of heating fluid.

In continuous processes the heat supply and demand are, on the average, equal. The effect of the thermal capacity on momentary fluctuations is determined by the amounts of stored heat absorbed or released during a temperature-fluctuation in comparison with the steady-state heat quantity. Obviously, if the storage heats (products of thermal capacities by temperature-fluctuations) are negligible in comparison with the steady-state heat quantity, their effect on control is insignificant. When, however, the storage heat is an appreciable quantity, as is usually the case, the effects of thermal capacity must be carefully considered. In batch processes the heat balance approaches the limiting case where all of the heat requirement is storage heat.

Simple Heat-Exchangers.—Let us now consider some typical simple liquid-liquid heat-exchangers, each with the same demand conditions and same heating surface, but with different thermal capacities and directions of flow. Fig. 83 (*a*) represents a simple concentric-tube (pipe within a pipe) exchanger connected for countercurrent, or opposed-flow operation, with the small inner pipe on the supply side and the large annular space on the load side. The temperature-sensitive element S is placed in the outlet of the exchanger, or in the pipe immediately adjacent thereto. In this heat-exchanger a temperature-change, as a result of any upset in the balance of heat demand and supply, reaches S in a minimum time. Consequently, with on-and-off control, the heat input pulses are of short duration and correspondingly small in amplitude. The small quantity of heat available from the low capacity on the supply side of the heat-exchanger, as the control valve shuts at the end of a cycle, is able to raise the temperature of the high capacity on the demand side only a slight amount before it declines again under the influence of new material flowing into the demand side of the heat-exchanger. Obviously, at higher loads the overshoot is reduced and the decline



(*a*) (*b*) (*c*) (*d*) (*e*) (*f*)

FIG. 83.—Some forms of heat-exchangers.

in temperature follows more quickly, with corresponding improvement in accuracy of control. Conversely, at lower loads the cycles are worse. Thus we see why a very much underloaded heat-exchanger on open-and-shut control may cycle badly, while when adequately loaded it controls very closely.

Similarly, with proportional control the heat exchanger shown in Fig. 83 (*a*) controls accurately. The heat-exchanger can follow rapid control changes without hunting. The favourable capacity attenuates temperature fluctuations, thus tending toward stability. As before, at light loads the effect of fluctuations is magnified, thus tending toward instability. For this reason a very much underloaded heat-exchanger on proportional control may also break into a cycle.

Fig. 83 (*b*) represents an exchanger exactly similar to that shown in Fig. 83 (*a*) except that the sensitive element is moved some distance away from the heat-exchanger. The time for a temperature-change to reach position S^1 is much greater than that taken to reach S. With on-and-off control, the on-and-off periods are correspondingly lengthened and the resulting cycle amplitude is greatly enlarged. With proportional control, the control-band must be much wider than before to make the belated valve-corrections less violent and to allow a wider range for deviations before the limits of proportionality are reached. Thus, with either type of control a large " transportation lag " entails poorer control.

It is also interesting to note that poor heat transfer in the heat-exchanger, or slow response of the thermal system, has an effect somewhat similar to transportation lag, which may be called " transfer lag." Insufficient or dirty heat-exchange surface and poor film coefficients from inadequate velocities result in high resistance to heat transfer, correspondingly high thermal potentials between the sides of the exchanger, and ensuing control difficulties. Similarly, short and thick or heavy bulbs in air or other poorly conducting media, and restricted circulation past the element can produce a large transfer lag to the thermal element and delay its response surprisingly. This is serious, since the thermal-element response should always be rapid in comparison with the process it is controlling.

Transportation lag and transfer lag together comprise the " response lag " of the system. Response lag, meaning the interval between initiation of a temperature-change and the initiation of a corrective response, must be kept small for best control. Transfer lag is reduced by increased thermal potential; whence, in cases of extreme transfer lag, normally unfavourable capacity-ratios may control better, since the thermal potential available for control has not been attenuated. Transportation lag is unaffected by thermal potential, being reduced only by reduction of the time interval, as by re-location of the thermal element, by reduction in preceding volume, or by increase in flow velocity.

Fig. 83 (*c*) represents another exchanger similar to that shown in Fig. 83 (*a*) but with the load and supply sides interchanged. The small central pipe is now the demand side, while the large jacket space is the supply side. The ratio of thermal capacities of the demand and supply sides of the exchanger has been greatly altered. With on-and-off control, the cycles are very large. The heat available from the large capacity on the supply side of the exchanger after the control valve closes causes a temperature overswing in the small capacity of the load side many times that which results in the case represented by Fig. 83 (*a*). A large capacity on the load side is favourable, diminishing and smoothing out the variations; on the supply side it is unfavourable, amplifying the variations. With proportional control the situation is likewise unfavourable, wide-band control being required for stability.

Heat-storage effects depend not only on thermal capacity: temperature levels are also significant. When the temperature-difference is large, the quantity of heat potentially transferable is large, and difficulties are accentuated. With on-and-off control, cycle amplitude is large; with proportional control, cycling can be avoided only by wide-band control with the attendant disadvantages. A small temperature-difference is conducive to good control; and sometimes, when little else is possible, merely reducing temperature-difference will improve controllability greatly. In milk pasteurizers, for example, the milk is heated not by steam directly, but by circulated water heated to a controlled temperature only slightly higher than the setting of the milk temperature-controller. Large transfer lag is always to be avoided because it requires large temperature-differences or thermal potentials which can produce large overswings.

Fig. 83 (*d*) represents the co-current, or parallel-flow type. Except for the direction of supply-medium flow, it is similar to the case represented by Fig. 83 (*a*), but this single difference is quite significant. Not only is the transportation lag obviously increased over its value in the former case, but also the transfer lag is greater. In a co-current heat-exchanger, the media approach the same outlet temperatures. A co-current exchanger is a " temperature leveller," and the average temperature-difference is large. In a counter-current unit, the supply medium discharges near the demand-medium inlet temperature, and the demand medium discharges near the supply-medium inlet temperature. A counter-current exchanger is a " temperature exchanger," and the average temperature-difference is small. Like counter-current heat exchange, co-current is also adversely affected by unfavourable thermal capacity.

Mixed-Current Heat-Exchangers.—Many heat-exchangers are neither counter-current nor co-current, but a mixture of the two types. Usually, the transportation lag is excessive and the transfer lag greater than need be, with poor controllability the result. Mixed-current heat-exchangers may be classed with co-current as difficult to control. In the bent-tube types they may be even worse than co-current, because fluctuations in supply or demand may cause local temperature-deviations simultaneously in the several passes. Successive responses of the thermal element to these deviations tend toward further upsets.

The simple heat-exchangers represent most of the common temperature-control problems. Less numerous, but important in many processes, are the many variations of the compound heat-exchanger types.

Compound Heat-Exchangers.—A typical multiple exchanger is represented by Fig. 83 (*e*). Two supply sections operate simultaneously and independently on the demand section. Similarly, multiple-demand sections are possible. In multiple exchangers, the supply or demand sections, no matter how many, act in multiple and their effects are additive.

Compound heat-exchangers may also be arranged with several sections in tandem or series, as shown in Fig. 83 (*f*). Here the intermediate section or sections introduce additional thermal capacity and additional transportation and transfer lags. Heat must be transferred to, traverse, and be transferred from the intermediate section or sections. Sluggish response is the normal characteristic of a series exchanger, and wide-band control is required. Fractionating columns are typical tandem heat-exchangers.

Very complex heat-exchanger systems are often encountered, particularly in processes where the several steps are interconnected by heat-recovery exchangers. These complex systems can be resolved into combinations of the simple and compound types previously discussed.

Favourable Factors for Controllability.—It follows from the above that the factors favourable to precise control, as reflected in smaller cycles with on-and-off control and in narrower control-bands with proportional control, are :—

(1) Minimum transportation lag ;
(2) Minimum transfer lag ;
(3) Minimum temperature-difference ;
(4) Minimum supply-side thermal capacity ;
(5) Maximum demand-side thermal capacity.

The converses are unfavourable, and are to be avoided in good design and operation since, with simple control, they result either in large cycles or in wide control-bands and consequent wandering.

Effect of Various Heat-Exchange Media.—Examples of liquid-liquid heat-exchangers have been discussed, but the cases of liquid-solid, gas-solid, gas-liquid, and gas-gas heat-exchangers must be considered also. When a solid is substituted for a liquid on one side of an exchanger system, the thermal-capacity ratio may not be greatly changed, as ordinarily the higher specific gravity of the solid is offset by a lower specific heat.

The problems with a solid are more likely to involve homogeneity and accurate sensing of temperature than transportation and transfer lags. When the supply medium is a hot gas, such as air, instead of a hot liquid, such as water, the temperature-difference may be considerably greater, yet result in a lower thermal capacity on the supply side with a net favourable effect on controllability. Conversely, when the substitution of a gaseous medium is on the demand side, controllability is unfavourably affected. With a vapour such as steam, the latent heat offsets in part the effect of the smaller mass.

In a plain-pipe air heater, the heater mass is so large compared with that of the air being heated that the system is always that represented by Fig. 83 (*c*). Therefore, proportional wide-band control is used. When, in addition, a sluggish thermal element is used, the results will be extremely bad. The control-band will be so wide that reset is imperative. On the other hand, in a finned-tube heater of equivalent rating the heater mass is much smaller, and the system may approximate that shown in Fig. 83 (*a*). Then, provided that the controller—thermal element, control mechanism, and valve—is extremely responsive, on-and-off or narrow-band control can be used. When the controller is not sufficiently responsive, the system is the less favourable one shown in Fig. 83 (*b*), requiring wide-band control with its attendant problems. To avoid needless handicaps, it is essential that controller response be more rapid than process response. Nowhere is this better illustrated than in air heaters.

Classification of Special Types.—Care should be exercised in classifying units which at first appear complicated, in that by analysis they may be placed in a simpler or other category. For instance, in a conveyor-drier or tempering furnace, the circulating air or products of combustion, respectively, are controlled in temperature by regulation of the heating medium supplied to coils, or by the regulation of combustion. The thermal capacity on the supply side is very large compared with the capacity of the circulating medium, which suggests " wide-band control." The resulting temperature of the load, however, is the significant operating temperature, the load usually having a considerable thermal capacity, sometimes exceeding the thermal capacity of the supply side. This, therefore, is of the tandem heat-exchanger type similar to that shown in Fig. 83 (*f*), and if the ratio of demand-side heat storage to supply-side heat storage is high, the system can be operated by on-and-off control. The load temperature is controlled precisely by controlling roughly an intermediate transfer temperature.

Reference to Chapter XVII.

HAIGLER, *Trans. Amer. Soc. Mech. Engineers*, 1938, **60**, No. 8, 633-640.

APPENDIX

THEORETICAL CONSIDERATIONS OF TEMPERATURE-CONTROL.

As indicated in the preface to this edition, there have been, in recent years, many attempts to evolve an analytical theory of temperature-control. None, however, appears to be completely satisfying as yet. While the theoretical foundations are old and the fundamental principles can be found in classical texts on the sciences, analytical methods have not yet penetrated properly into the field of temperature-control.

Most of the mathematical analyses are based on analogies with existing principles of Physics or Mechanics. The most frequent method of treatment of the subject is to consider control processes in general and to refer to temperature-control as an individual member of these processes. German theorists[1] have attempted to correlate the theory of speed governors in turbines and steam engines with process control, whilst British and American writers draw on hydraulic analogies. The application of hydraulic analogies to heat transfer by convection is fairly satisfactory, but similar analogies for heat transfer by the agencies of conduction and radiation are not so, and these latter are best dealt with in a conventional manner.

The aim of the theorists is to evolve a mathematical equation, or equations, which will express the effects of a number of changes in certain factors on the system.

In some cases the method of attacking the problem is to subject the system to what is termed a "standard disturbance" by moving a valve or other unit by a definite amount, deducing the effects of such a change on the system, and expressing the results in the form of an equation.

It will be readily appreciated that if reactions took place instantaneously, the element of time would not need to be considered, and the relation between the position of the regulating valve and the temperature in heat-control would be a simple and direct one. The temperature would move from one position of equilibrium to another without oscillation. Unfortunately, this ideal condition is not attained, although approximations are possible. The heat capacity of the system enters into the problem, involving time-relations. Reacting causes and effects have to be considered, and attempts are, therefore, made to express all these causes and effects mathematically by differential equations of varying order. In general, the differential equation is raised about one degree for each such cause and effect. The justifiable assumption is made that the factors involved have a linear relationship, in order that the differential equation shall be linear and more readily solved. It may be interposed here that the most usual equation is of the type which describes vibrating systems ; but such an equation is, obviously, of no value until reduced to a specific form and its coefficients evaluated. The effectiveness of control can then be specified in terms of time-constants. One such general equation is as follows :—

$$C_n \frac{d^n \varphi}{dt^n} + C_{n-1} \frac{d^{n-1} \varphi}{dt^{n-1}} \quad . \quad . \quad . \quad C_2 \frac{d^2 \varphi}{dt^2} + C_1 \frac{d\varphi}{dt} + C_0 = 0\,;$$

this can be reduced to a simple second-order form in the case of temperature-control, as follows :—

$$C_2 \frac{d^2 \varphi}{dt^2} + C_1 \frac{d \varphi}{dt} + C_0 = 0,$$

where φ is the fractional deviation of the temperature from its standard value $\frac{(T - T_a)}{T_a}$.

Further reference will be made later to this aspect of the subject. It will be convenient to adhere for the moment to processes in general, as has previously been indicated is the custom in dealing with the mathematical aspect of processes of which temperature is one.

Referring again to the capacity of a system, it may be said in general terms that whenever the absorption of energy occurs, there must be a resistance to the flow of energy from this part of the process ; otherwise the storage of energy would be impossible, regardless of the amount supplied. Thus with each capacity there is always associated at least one "resistance." Process lags occur as a result of combinations of these capacities and resistances. Three types or classes of process lags have been recognized,[2] as follows :—

(1) *Capacity Lag*—a retardation (not a delay) of the condition of a given process variable, resulting from the ability of the immediate part of the process to absorb and store up energy.

(2) *Transfer Lag*—a retardation (not a delay) of the condition of a given process variable, following an instantaneous change in some related variable, itself resulting from resistance offered to the flow of energy between two or more reasonably isolated capacities of the process.

(3) *Distance-velocity Lag*—a direct delay or postponement of the beginning of a change in a given process variable, following an instantaneous change in a related variable at some other point in the process, itself resulting from any characteristic

of the mechanical embodiment of the process which requires time to conduct the effect of the change to a part of the process whence it may affect the given variable.

A process possessing "Transfer Lag" must consist of at least two capacities. "Distance-velocity Lag" is the only type of lag expressible in time units. "Capacity Lag" and "Transfer Lag" come under the heading of functional time-lags. "Distance-velocity Lag" may be termed finite time-lag.

Most German authorities on regulation use dimensionless quantities. Changes which take place are represented by their ratios as compared with some fixed value, either the average or the maximum, rather than their actual values. The final equations are then expressed in terms of ratios (dimensionless quantities) and time. By this means the form and use of the mathematical relationships is simplified. The results, however, can readily be converted to absolute quantities when required.

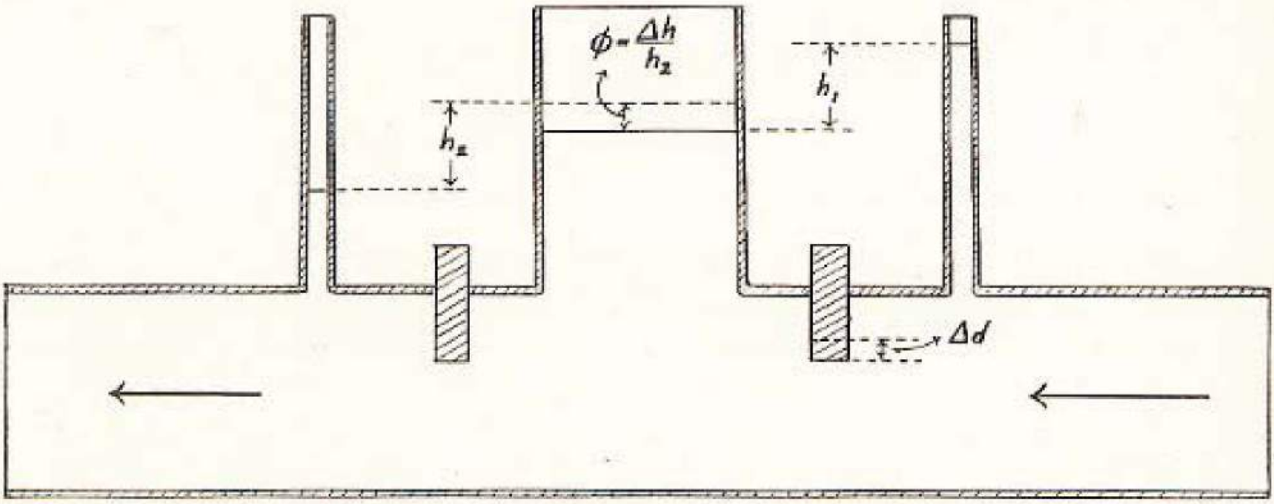


FIG. 84.—Hydraulic analogy of a "single-capacity" process.

Hydraulic Analogy.—As previously stated, British and American writers use a diagrammatic representation of a process, based on hydraulic principles. Fig. 84 illustrates a simple diagram of this form and refers to a so-called "single-capacity process." By interpretation and extension, this type of diagram can be made to represent various forms of temperature-regulation problems, bearing in mind the limitations previously expressed.

The process is considered to be a series of capacities separated from one another by resistances, so that flow from one capacity to the other is accompanied by a decreased energy level, represented by a difference in liquid levels (Fig. 84). The flow through the resistances may be made proportional to the difference in levels ("differential head"), since the flow of heat is inversely proportional to the resistances in its path. The area of the tank represents the capacity of the system or B.Th.U.'s per degree. This can be considered as the product of the specific heat of the material being heated times its mass, provided that the range of temperature is such that the specific heat remains constant.

If the supply valve is moved suddenly at time $t = t_0$ by an amount Δd, the increased input flow would, according to the German system of dimensionless quantities, be $\frac{\Delta Q}{Q}$, where Q is the flow rate at equilibrium valve position. A change in level h_2 results, represented by a change $\frac{\Delta h}{h_2} = \varphi$, where h_1 is the differential across the supply valve, and $h_2 =$ the differential across the discharge valve. The rate of change of level, or φ^1, is directly proportional to the increased input flow or disturbance q, and if q remains constant φ^1 also remains a constant. The ratio of φ^1 to the corresponding value of q_1 is a characteristic of the system of regulation and has been called by Neumann[3] the "sensitivity of the regulating space." The reciprocal of this ratio, or $\frac{q_1}{\varphi^1}$, has been called *Anlaufzeit* by German writers, a term which has been variously translated as "application lag," "process-time," "starting-time" and "reaction-time."

The process just considered has been referred to as a "single-capacity" process; as previously indicated, multiple-capacity processes are possible. The latter may be subdivided into the following groups :—

(*a*) Capacities and resistances in series,
(*b*) Capacities and resistances in parallel, and
(*c*) Series-parallel combinations.

Many multiple-capacity systems can, however, be approximated by a single-capacity system with sufficient exactness.

Mathematical Theories of Temperature-Control.—Some of the principal features of specific mathematical theories advanced by various authors may now be considered. For a full description of these theories the reader is referred to the original papers on the subject, to which references are given at the end of this chapter.

Callender[4] and his collaborators discuss the question of time-lag in its relation to control systems in general. They consider that variation in the departure of the temperature from the normal or standard value may be due to three causes :—first, through uncontrolled disturbances, such as fluctuations in the ambient temperature, or variations of voltage on the mains from which the current for the heating coils is taken ; secondly, through the operation of the control gear ; and thirdly, apart from changes due to these causes, a departure of the furnace space temperature from the normal may in itself give rise to a variation of the temperature.

A general expression is given connecting these variations as follows :—

$$\frac{d\,\theta\,(t)}{dt} = D\,(t) + C\,(t) - m\,\theta\,(t) \quad . \quad . \quad . \quad (1)$$

where $\theta\,(t)$ is the departure at time t of the temperature from the set value ; $D\,(t)$ is the effect of uncontrolled disturbances and is regarded as a given function of t ; $C\,(t)$ is the effect at time t of the operation of the control ; and $-\,m\,\theta$ is the inherent effect of variation of $\theta\,(t)$ from its zero value. Thus $D\,(t)$ is the disturbing function and $C\,(t)$ the controlling function. The uncontrolled disturbances do not affect the control directly, but through variations of θ, to which they give rise. For a system with time-lag, the function $C\,(t)$ then depends on the behaviour of θ not at time t, but at a time $t - T$, where T is the time-lag, which is assumed to be constant.

The effect of the control at time $t + T$ is determined by the behaviour of $\theta\,(t)$ at time t. The dependence of $C\,(t + T)$ on $\theta\,(t)$ expresses the behaviour of the control, which may be put into the following form, termed the " law of control " :—

$$-\,C\,(t + T) = n_1\,\theta\,(t) + n_2\,\dot{\theta}\,(t) + n_3\,\ddot{\theta}\,(t) \quad . \quad . \quad (2)$$

where the dots denote differentiation with respect to time, and n_1, n_2, and n_3 are constants. For satisfactory control these constants must lie within certain limits of value. By using different values of these constants, the behaviour of the control from the point of view of sluggishness and damping, etc., can be determined.

In their analysis, Callender and his collaborators assume the time-lag to be unity and write—

$$t/T = \tau,$$

and $\quad m\,T = \mu, \quad n_1\,T^2 = \nu_1, \quad n_2\,T = \nu_2, \quad n_3 = \nu_3$;

ν_1, ν_2 and ν_3 being called the " control-constants " of the system.

$TD\,(t)$ is taken as equal to $\psi\,(\tau)$,
and $TC\,(t)$,, ,, ,, $c\,(\tau)$.

$\psi\,(\tau)$ is referred to as the disturbing function. For θ is written $\theta\,(\tau)$, regarded as a function of τ rather than of t.

From this, equations (1) and (2) become—

$$\frac{d\,\theta\,(\tau)}{d\tau} = \psi\,(\tau) + c\,(\tau) - \mu\,\theta\,(\tau) \quad . \quad . \quad . \quad (3)$$

$$-\,\frac{dc\,(\tau + 1)}{d\tau} = \nu_1\,\theta\,(\tau) + \nu_2\,\frac{d\,\theta\,(\tau)}{d\tau} + \nu_3\,\frac{d^2\,\theta\,(\tau)}{d\tau^2} \quad . \quad (4)$$

Three methods of investigation were used to study the equations, as follows :—

(i) The determination of the "normal modes" of the equations. The behaviour of $\theta(\tau)$ where $\tau = t/T$, the time-lag T being a unit of time, is exponential or damped-harmonic, and the frequencies of the modes and damping constants are found.
(ii) The use of Heaviside operators. The equations (3) and (4) can be expressed in such a manner as to form a pair of linear difference–differential equations with constant coefficients. These are then treated by the Heaviside operational method.
(iii) Numerical investigation of particular cases by arithmetical or graphical methods, or by the use of a differential analyser.

To deduce the true ranges of suitable "control-constants" a genuine time-lag is assumed, instead of a mere sluggishness of starting, analogous to inertia.

The physical significance of the "law of control" can be illustrated by considering the control of temperature by steam-heating, the steam supply being controlled by a valve. The setting of the valve determines the controlling function, and from the "law of control" with $n_1 \neq 0$, it follows that not the valve-setting itself, but its time rate of change, depends on the value of the temperature and its derivatives, so that the valve-setting depends not only on the behaviour of the temperature at any particular instant, but on the time-integral of the temperature, and so on its previous history.

Diagrammatical representation of this method of control is shown in Fig. 85. The valve S governs the supply of steam to a vessel whose temperature-deviation θ from the correct value is indicated by the position of the arm A. The value of θ is to be kept as small as possible. The value $S(t)$ depends on the setting of the valve S at time t, and the equation expressing the "law of control" becomes

$$-S(t) = n_1 \theta(t) + n_2 \dot{\theta}(t) + n_3 \ddot{\theta}(t) \quad . \quad . \quad (5)$$

The valve S should be moved automatically so that $S(t)$ satisfies this equation. In Fig. 85 let x be the height of the lower end U of a rod hanging from the arm A above its position when $\theta = 0$, and suppose x is proportional to θ. Let y be the height of a cylindrical vessel W_2 above some arbitrary level, this height being made proportional to the value of $-S(t)$ by means of a connection to the valve S through a cam as shown. A similar vessel W_1 is placed so that the contact U can touch the surface of the liquid in W_1. The liquid in W_2 passes through a siphon pipe, from an intermediate point Q of which a branch pipe is led to a dish D, of large cross-section compared with those of W_1 and W_2, so that changes of level of the liquid in D can be neglected. This level is adjusted to be that of U when $\theta = 0$.

If the mechanism M, actuated by the contact at U, causes S (and so W_2) to be moved in such a way that the liquid surface in W_1 is kept just in contact with U, then if the cross-sections of W_1 and W_2 are C_1 and C_2, and the resistances of the pipes from Q to D, W_1 and W_2 are R, r_1 and r_2 respectively, then it follows from the equations of motion and continuity of the liquid that

$$\dot{y} = \frac{1}{C_2 R}\left[x + \left\{(R + r_1)\,C_1 + (R + r_2)\,C_2\right\}\dot{x} + \left\{R\,(r_1 + r_2) + r_1 r_2\right\} C_1 C_2 \ddot{x}\right] \quad . \quad . \quad (6)$$

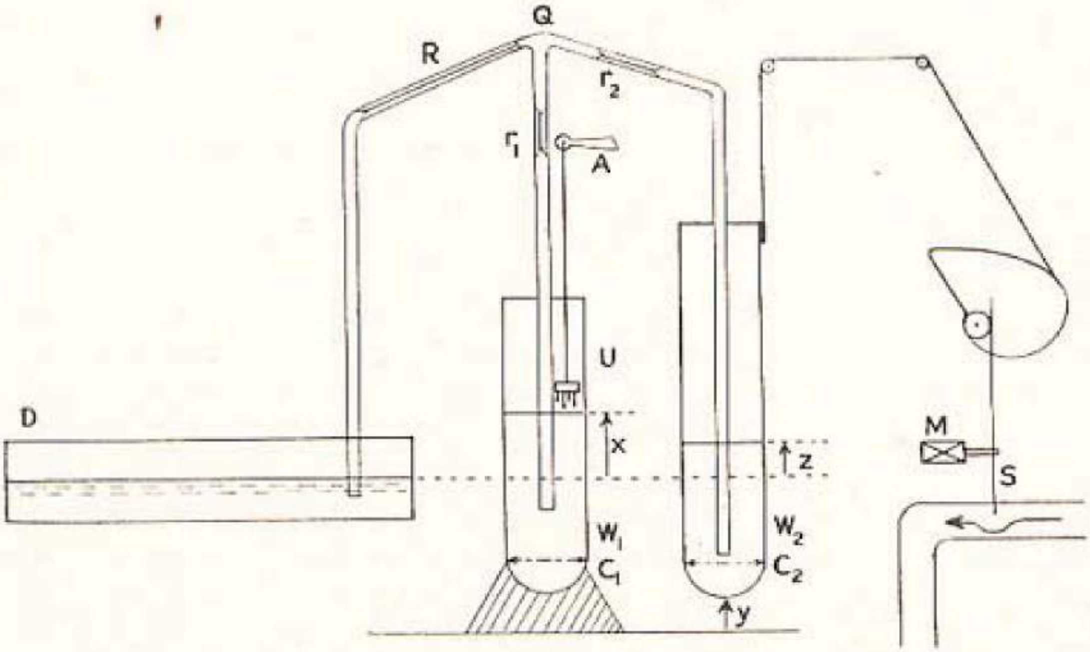


FIG. 85.—Diagrammatical representation of the control law.

This equation satisfies the " law of control," being of the same form, since x and y are respectively proportional to $\theta\,(t)$ and $-\,S\,(t)$.

Thus, if contact of the surface of the liquid in W_1 with U is maintained as θ varies, a law of control of the desired form is obtained. This means that the controlling mechanism only acts at any instant in proportion to the amount of deviation from the set temperature.

The curves relating deviation with time will, after a thermal disturbance of the system, show a gradual return to the normal temperature without continued oscillation.

This form of the " control law " may be extended a stage farther.[3] An auxiliary variable $z\,(t)$, related to $\theta\,(t)$ by the equation

$$\dot{z}\,(t) + B_1\,z\,(t) = B_2\,\dot{\theta}\,(t) + B_1\,\theta\,(t) \quad . \quad . \quad (7)$$

can be introduced into the equation.

The law is then expressed in the form

$$-\dot{c}\,(t+T) = n_1\, z\,(t) + n_2\, \dot{z}\,(t) + n_3\, \ddot{z}\,(t) \quad . \quad . \quad (8)$$

This law reduces to the former control law (2) if $B_2 = 1$ or $B_1 \to \infty$, B_2 remaining finite; but in the case under consideration $B_2 > 1$.

To apply this law in practice, the principle of the control can be illustrated diagrammatically as before. In Fig. 86 the displacement $x\,(t)$ of the indicating arm A indicates the deviation from the set temperature, and so is proportional to $\theta\,(t)$. The control law (6) will be attained if the same mechanical means of obtaining the relation (2) is used, but the displacement $x\,(t)$ is now made proportional not to $\theta\,(t)$ but to $z\,(t)$, related to $\theta\,(t)$ as explained above.

Fig. 86 shows the principle of an electrical means of attaining conformity to the law.

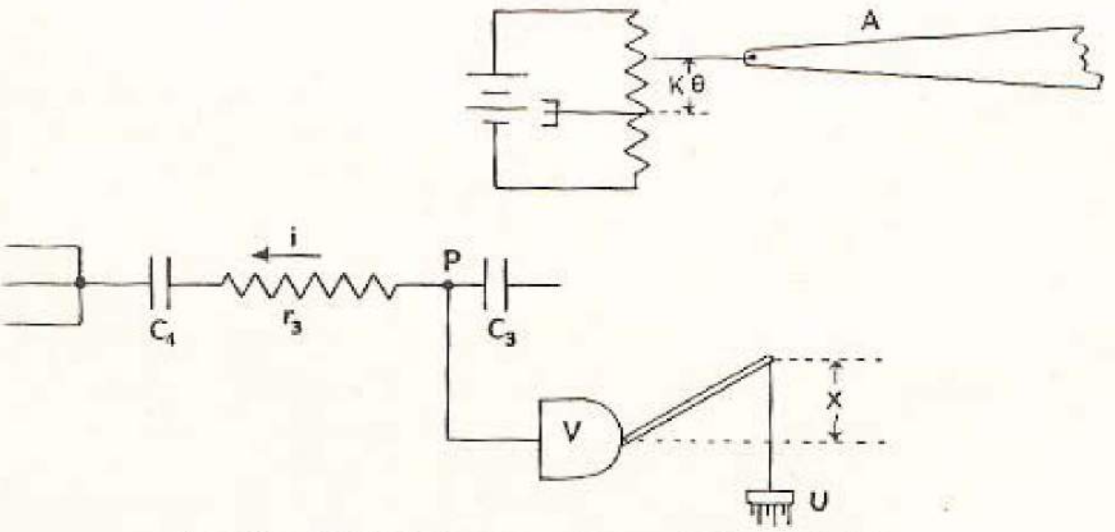


FIG. 86.—Electrical representation of the control law.

Here U is a movable group of contacts and A is the indicating arm of the thermometer. These two components are the same as in Fig. 85. In Fig. 85, however, U was suspended directly from A, so that the displacement x of U was directly proportional to the temperature-deviation θ. This direct mechanical connection is replaced by a connection through the electrical circuit shown, A moving a contact over a potentiometer and U being suspended from the indicating arm of a voltmeter V which measures the potential at the point P of the circuit (in practice a thermionic voltmeter is usually employed).

If $K\,\theta$ is the potential tapped off on the potentiometer, V_p the potential at P, and i the current in the direction indicated in the diagram, we have

$$\left(\frac{1}{C_3} + \frac{1}{C_4}\right)\int i\,dt + r_3\, i = K\,\theta,$$

and
$$\left(\frac{1}{C_4}\right)\int i\,dt + r_3\,i = V_p\,;$$

whence, eliminating i,

$$\frac{d\,V_p}{dt} + \left(\frac{1}{r_3}\right)\left(\frac{1}{C_3}+\frac{1}{C_4}\right)V_p = K\left[\frac{d\,\theta}{dt} + \left(\frac{1}{r_3\,C_4}\right)\theta\right] \quad . \quad (9)$$

so that the voltmeter deflection x, which is proportional to V_p, satisfies a relation of the form (8). The values of B_1 and B_2 in (2) can be adjusted by choice of scales and of r_3, C_3, C_4.

The remainder of the control apparatus, namely, that portion of it which gives the relation (2) between z and the controlling function C, is the same as that of Fig. 85, with the simplification that the vessel W_1 could be moved directly from S, and W_2 omitted. A mechanical, hydraulic, or electrical method can be used to obtain the relation (2), independently of the type of method used to obtain the relation (7).

Turner,[6] in order to determine the mathematical relationship between the sensitive element and the heating element, designed a special form of experimental oven. It consists of a metal cylinder of length l_1 and cross-sectional area A. The "slave" coil, as he terms it, or heating element, and the "master coil" or sensitive element encircle this cylinder; the slave coil at the bottom being separated from the master coil by a distance l up the cylinder. The heating power P_1 in the slave coil is controlled by the temperature θ of the master coil. The rate of change of power input with temperature, or control sensitivity, is a known variable. When the control sensitivity is made large, thermal oscillation takes place, due to the slave and master coils mutually affecting each other thermally. Analysis shows that if $l = l_1$, or $< 0{\cdot}55\,l_1$, thermal oscillation arises when the control sensitivity per unit area of cross-section, $-\frac{1}{A}\cdot\frac{d\,P_1}{d\,\theta}$, is increased beyond a critical value S, where $S = 17{\cdot}6\ K/l$, or $35K/l$, respectively. In both cases the period of oscillation is

$$T = \frac{0{\cdot}57\,l^2\rho c}{K},$$

where K is the thermal conductivity of the material of the cylinder, ρ its density, and c its specific heat.

As indicated above, Turner analyses the condition where S is just equal to $-\frac{1}{A}\cdot\frac{d\,P_1}{d\,\theta}$, and does not consider the case where S is much less than that value. In the latter case it is anticipated that the curves relating the thermal changes with time would be different in character from, and sharper than, those obtained when S is equal to the value.

Turner does not devote much attention to the amplitude of oscillation, but considers mainly the frequency of oscillation. From experiments with his special oven he concludes that large oscillation frequency and small oscillation amplitude go together.

Where the master and slave coils are intermingled regularly, as in certain forms of thermostat furnaces, conditions defined by the equation $S = 35\,K/l$ (which applies in this case) produce the greatest control sensitivity. Turner states that to effect this and avoid self-oscillation altogether, or, if oscillation cannot be avoided, to make T as small as possible, the master and slave coils should be in close juxtaposition and should be wound in good thermal contact with a chamber of high conductivity. $K/\rho\, c$, which is the diffusivity of the material, should be as large as possible.

The effect of the thickness of the wall of the chamber on penetration by the hunting oscillation is expressed by the ratio between the amplitudes at the two surfaces of the wall, which ratio is

$$\frac{l\,h}{2} \cdot \sqrt{\frac{\omega}{2\,\sigma}},$$

where h is the wall thickness, $\omega/2\pi$ is the hunting frequency, and $\sigma = K/\rho\, c$ the diffusivity of the material.

A thick wall is therefore desirable for two reasons: to reduce "hunting," and to reduce temperature-gradients along the walls.

Turner considers that hunting is necessarily present if the heat supply is controlled in discrete quantities, and is also present when a continuous relation exists between temperature and heat supply, provided the control sensitivity exceeds a certain critical value. That is, stability of control is not necessarily improved merely by increasing the sensitivity of the temperature-sensitive device. (The natural limit to the sensitivity of all measuring processes has been analysed by Barnes and Silverman.[7])

It may be said here in brief that the necessary qualities of automatic temperature are stability, reliability, and sensitiveness, in the order named. A sensitive control which hunts is of no use, whilst a sensitive and stable control which is not reliable is also of little value.

Turner assesses the specific effectiveness of the thermostat by a figure of merit, represented by the ratio between the change in temperature of the furnace enclosure if there were no thermostatic control, and the change of temperature which *does* occur with thermostatic control. He assumes that two factors, only, affect the constancy of temperature, viz. change of ambient temperature, and electrical power-supply variation. Assuming steady conditions, the figure of merit

$$\eta = \frac{N_1 + N_2}{N_1} \simeq \frac{N_2}{N_1},$$

where N_1 is a constant related to the power emitted from the furnace (by conduction, convection, and radiation), $N_1(\theta - \varphi)$ is the value of this power when θ is the furnace temperature and φ the ambient temperature, and

$$N_2 = \frac{\delta P_1}{\delta\theta},$$

where P_1 is the heating power in the slave coil (*i.e.* controlled by the master coil).

It is deduced that the higher the temperature of the furnace the easier it is to obtain a large figure of merit; and further, that the attainment of a large figure of merit is not dependent on the provision of good thermal insulation between the furnace and its surroundings. The advantage accruing from insulating the furnace appears to lie in the reduction of power required to maintain the desired furnace temperature.

Ivanoff[8] obtains numerically the frequencies, dampings and amplitudes, etc. of particular cases and deduces a " law of response " to the controlling mechanism. A regularly-repeated disturbance is introduced in order to give a basic periodicity to which Fourier's analysis is applied. Ivanoff introduces the term " potential temperature," defined as " the limiting value of the temperature-change which the plant [meaning temperature-controlled system] tends to attain for a given alteration in the position of the controls "; the " controls " being fuel valves, dampers, etc.

He discusses the oscillations of temperature—potential as well as actual or recorded temperatures—which are produced when the sensitivity of the controller is increased to a point where a periodic oscillation of sinusoidal form occurs. Equations are derived to express the conditions for stability for " on-and-off," proportional, and floating methods of control.

Ivanoff likens time-lag to the action which occurs when heat flows into a semi-infinite solid. If the temperature of a control mechanism at the surface of the solid is made to very periodically so that

$$\theta = A \sin mt,$$

where A is the amplitude and $\sin mt$ the controlling disturbance, in which

$$m = \frac{2\pi}{\text{period of oscillation}},$$

then the recorded temperature is

$$A\,e^{-c\sqrt{m}} \sin(mt - \sqrt{cm}),$$

where e is the base of natural logarithms and C a time indicating the amount of lag that is characteristic of the system.

Further references[9-15] to discussions on the subject of the theoretical foundations of temperature-control are listed below.

References to Appendix.

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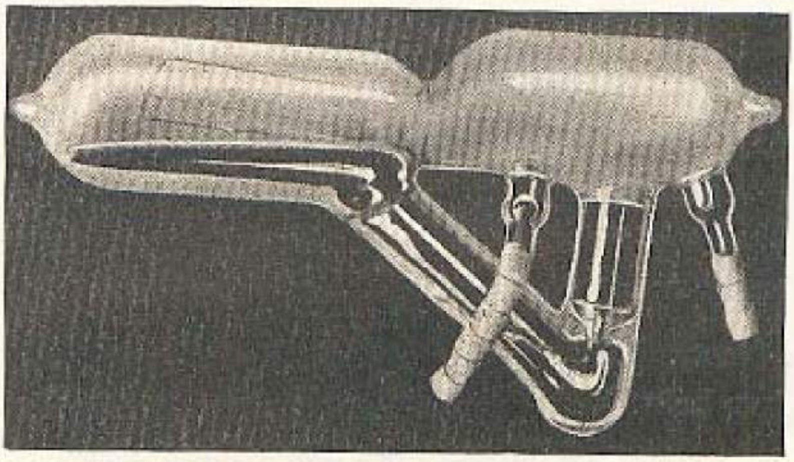
MERCURY SWITCHES



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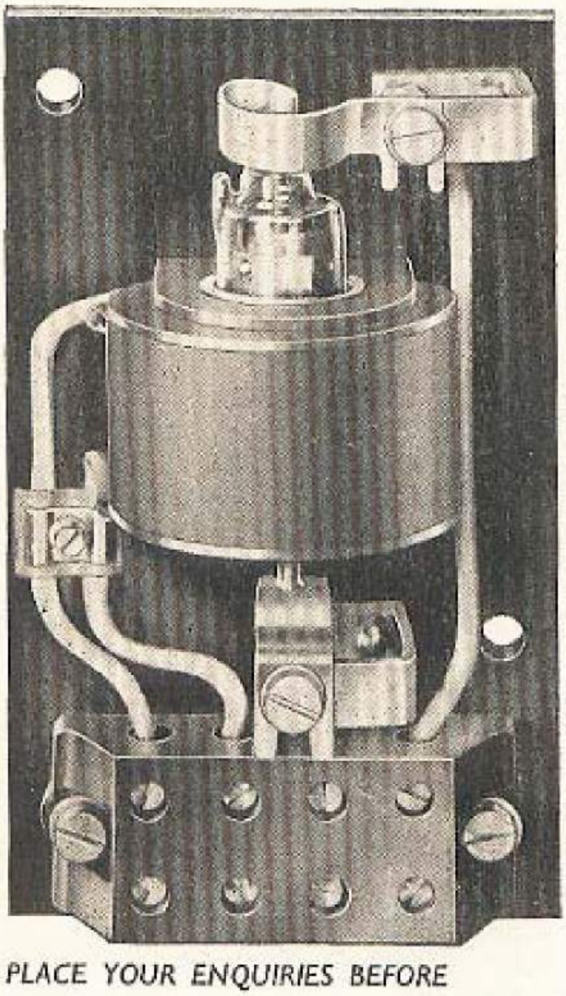

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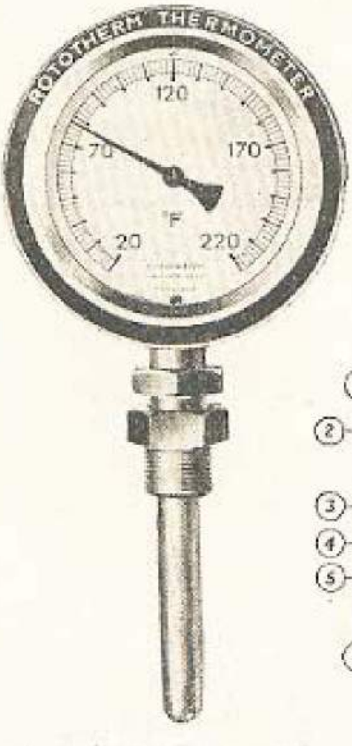

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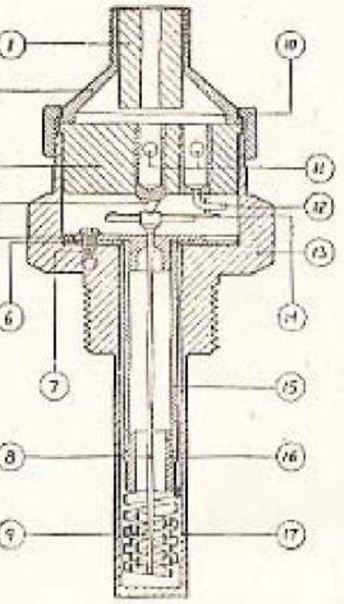

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